CONFIDENTIAL

COPY NO. 64

CONTRACT REQUIREMENTS	CONTRACT ITEM	MODEL	CONTRACT NO.	DATE
Exhibit E Section 5.1	Line Item 024	LEM	NAS 9-1100	14 Jan 63

TYPE II

Pri. 750

265-10688

REPORT

NO. LED-570-5 DATE: 10/3/63

DOCKING SIMULATION I-A1

FINAL REPORT [U]

CODE 26512

Joseph Russo / N. Freeberg

PREPARED BY:
J. Russo, Systems Simulation
N. Freeberg, Crew Systems

H. Sherman

CHECKED BY:
H. Sherman, Crew Systems

A B Whitaker

APPROVED BY:
A.B. Whitaker, LEM Systems Project Engineer
R.W. Kress — R.W. Kress, Systems Simulation

REVISIONS

DATE	REV. BY	REVISIONS & ADDED PAGES	REMARKS
		CLASSIFICATION CHANGE	
		To UNCLASSIFIED	
		By authority of GDS-EO11652	
		Changed by Date 12/31/72	
		Classified Document Master Control Station, NASA Scientific and Technical Information Facility	

AVAILABLE TO NASA HEADQUARTERS ONLY

CONFIDENTIAL

GRUMMAN AIRCRAFT ENGINEERING CORPORATION

TABLE OF CONTENTS

TABLE OF CONTENTS Cont'd

TABLE OF CONTENTS Cont'd

SUMMARY

A preliminary study of a manually controlled docking maneuver was conducted with a six degree of freedom LEM Docking Simulator at the NAA Columbus Division, Columbus, Ohio.

Variations were introduced in the attitude and translation control systems which involved combinations of proportional (attitude hold mode) and minimum impulse for the attitude control, with direct (on-off) and minimum impulse for the translation control. A direct (on-off) mode for attitude control was not used because successful docking could not be accomplished with this mode.

Additional variations in study conditions involved vehicle weight (light vehicle of 4,210 pounds and heavy vehicle of 5,050 pounds) as well as RCS minimum impulse durations of 15 ms and 30 ms.

On the basis of docking performance measures and pilot ratings, there was significantly superior docking performance for the attitude hold mode with a minimum impulse translation control. The pulse duration of 15 ms jet firing for the minimum impulse mode resulted in significantly better performance with regard to fuel and lateral deviation at docking. Less fuel consumption and greater precision at contact was also achieved for the lighter (4,210 pound) vehicle than for the heavy one.

The lighter vehicle in conjunction with the longer minimum impulse duration, reduced terminal docking precision.

Pilots never exceeded the velocity performance criteria at docking and the proportion of failures to meet all other performance criteria were relatively low -- never exceeding 15% of the trials.

I. INTRODUCTION

Manual control of the LEM vehicle is likely to be the primary mode of operation for the terminal portions of the docking phase. The ability of the astronaut to accomplish this maneuver successfully, the performance limits within which it can be accomplished and the determination of optimum control techniques and other vehicle conditions which should be provided, constituted the study purposes for the Docking Simulation IA2 program.

The present report is based upon information derived from a fully manual lunar orbit docking maneuver, conducted with a fixed-base six degree of freedom simulator. Measures of vehicle performance and pilot evaluations constitute the data from which the major study results are drawn. Comparisons are made of system performance under the conditions chosen for study and values of the docking performance parameters are presented as an aid to system design.

In addition, certain qualitative observations are discussed for control techniques which did not allow successful docking trials and also for a preliminary study effort with a trapeze type of docking technique under which a limited number of runs were obtained with one pilot.

This simulation was conducted by GAEC at the North American Aviation facilities at Columbus, Ohio, during March and April of 1963.

II. METHOD AND PROCEDURE

A. DESCRIPTION OF THE SIMULATION

1. Simulator Equipment - A closed-circuit television system is used to present the pilot of the LEM vehicle with a six-degree of freedom motion picture of the Command-Service Module (Figure #B3). The pilot "flys" his mission while sitting in a full scale fixed-base cockpit which is installed in the projection room. He views a continuously changing video picture projected onto a screen in front of the cockpit.

Activation of the cockpit controls sends analog signals to the computer which, in turn, varies the panel instrument readings, causing a television camera to follow the exact flight path and attitude of the vehicle, and a star field generator and projector to follow the attitude commands. The TV camera views the Command-Service Module and duplicates the pilot's view as seen from the LEM. The picture of the CSM is transmitted to the projector and from there to the screen for display to the pilot.

2. Discussion of Equations - The basic assumptions involved in the derivation of the equations were as follows:

(a) The CSM was assumed to be in a circular lunar orbit.

(b) The relative distance between the LEM and CSM was assumed to be small compared with the CSM orbital altitude.

(c) Reaction jet fuel consumption during the docking mission was assumed to cause a negligible change in LEM mass, inertias, and C.G. position.

(d) The exhaust gases were assumed to have no angular velocity with respect to the LEM.

(e) Jet damping forces were assumed to be negligible.

(f) The reaction jets were assumed to have no thrust misalignment.

(g) The relative angular displacement between the LEM and CSM with respect to the moon center was assumed to be small.

(h) The inertial pitch, roll and yaw computations were deleted to conserve analog computer equipment.

A list of the initial conditions for the study are given in Table #B1 (Appendix B) and diagrams showing the location of the LEM with respect to the CSM is shown in Figures #B1 and #B2 (Appendix B).

3. Instrument Panel - The panel arrangement included the following instruments:

(a) Timer

(b) Range

(c) Range rate

(d) AAI - All Attitude Indicator

(e) Line of Sight Elevation

(f) Line of Sight Azimuth

(g) Translation Mode Switch - 2 Position (not functional)

(h) Reaction Control System Mode Select Switch - 3 Position (not functional). See Figure B4 for a picture of the panel.

4. Controls - A three axis fingertip controller was used to provide attitude control and is shown in Figure B5. It contained a position potentiometer and a pair of detent switches in each axis. The potentiometer provided proportional rate commands in the attitude hold mode. The detent switches synchronized the attitude follow-up function in the attitude hold mode or commanded jet firings in minimum impulse on direct modes. A thrust controller was used to provide translation jet firings along the x, y and z axes (see Figure B5).

5. Data Recording - Pilot opinion data based on NASA's Cooper Rating Scale was obtained following each of the runs. Twenty channels of data were continuously recorded from the analog computer on strip charts. Final values of the angular and translational displacements and velocities, flight time and propellant consumption were recorded by digital printout.

6. Determination of Simulator Control Parameters - Prior to collection of the test data, it was necessary to define a set of attitude control parameters (rate gyro gain, stick sensitivity and dead zone, etc.,) that would serve as the nominal conditions during the test runs. Ratings of system suitability were collected utilizing the Cooper Rating Scale and optimum control parameters were defined based on these ratings.

Among the control combinations that were to be considered in the original study plan, a direct (on-off) attitude control mode was planned. In addition, one other study condition that was to be considered consisted of runs to be made with a complete RCS jet quad failure.

The series of trial runs made with direct (on-off) or minimum impulse as a translation mode coupled with direct (on-off) as an attitude control mode resulted in failure to dock successfully on the part of the subjects.

For the series of trials with a complete quad failure using every type of mode combination there were, again, no successful dockings accomplished. The reason for this was apparent. The control logic as set up at this time could not cope with a quad failure.

6. Cont'd. Owing to these observations, the series of runs to be made were revised so that a quad failure or a direct (on-off) condition for attitude control were not used as study variables.

B. PROCEDURE

The study data were obtained from docking runs made by four pilots, two of whom are NASA astronauts and two of whom are aircraft test pilots. Each pilot received an indoctrination on the operation of the docking simulator. In addition, a series of pre-training trials was run by each pilot to a criterion of four successful docking trials using combinations of a proportional (attitude hold mode) or minimum impulse attitude control (right-hand) with a minimum impulse or direct translation control (left-hand).

Each pilot was instructed to achieve docking as quickly and accurately as possible with termination of a trial indicated by a green light in the cockpit. Criteria for a successful trial consisted of vertical and lateral velocities ($\dot{h}, \dot{z}$) no greater than 1 ft/sec; axial velocity ($\dot{s}$) no greater than 1.5 ft/sec; vertical and lateral displacements (h,z) less than 12 inches; angular displacements of no more than 10° and maximum angular velocities of less than 1°/sec.

Pilots could choose their own flight path nulling out translational deviations from the CM in any order desired. Any combination of visual and instrument approach techniques could be employed and for the majority of runs external visual information was primary, particularly in the final stages of docking.

C. STUDY PROCEDURES

1. Four sets of attitude and translation control combinations were selected as feasible for study. The types of controls used are as follows:

(a) Proportional (attitude hold mode) is a rate command mode with an attitude hold feature in the stick neutral position. This mode is used for attitude control only.

(b) Minimum impulse mode is an open loop type acceleration control mode providing the pilot with a pulse train of 2 pulses per second and a pulse width of either 6, 15 or 30 milliseconds. This mode is used for both rotational and translational precision control.

(c) Direct mode is an on-off open loop type acceleration control where the jets are either fully on or off.

The type of control combinations used are as follows:

(1) Minimum impulse attitude control with minimum impulse translation (MI-MI).

(2) Minimum impulse attitude control with direct translation control (MI-D).

(3) Proportional (attitude hold mode) attitude control with minimum impulse translation control (P-MI).

(4) Proportional (attitude hold mode) attitude control with direct translation control (P-D).

2. Vehicle Weights.

(a) Light Vehicle - 130.75 Slugs or 4,210 pounds.

(b) Heavy Vehicle - 156.85 Slugs or 5.050 pounds.

3. Minimum Impulse Control Pulse Duration.

(a) 15 milliseconds

(b) 30 milliseconds

4. Trapeze Type Docking.

Following the primary study runs, a preliminary evaluation was made of certain degraded and failure modes using a trapeze type of docking technique.

Restrictions in the availability of time and subjects allowed the use of only one highly trained experienced simulator pilot. Thus, this phase consists of essentially a qualitative evaluation for the purpose of defining feasible conditions for future GAEC docking studies.

Degradation was introduced in varying combinations:

(a) Breaks in the rate and/or attitude feedback loops under direct and minimum impulse translation modes (see Figure #B7).

(b) Loss of single RCS jets.

(c) Omission of the All Attitude Indicator (AAI) display.

(d) In the attitude hold mode by providing an on-off control element rather than linear control element (see Figure #B10).

D. <u>PERFORMANCE MEASURES</u>

Measures of LEM docking performance chosen for analysis were:

(a) Lateral deviations from the CSM docking hatch at trial termination in h and z.

(b) Translational velocities at contact with CSM, ($\dot{s}$, $\dot{h}$, $\dot{z}$).

(c) Total time for completion of the docking trial.

(d) Angular deviations from zero at contact with CSM (pitch, roll and yaw.)

(e) Total RCS fuel consumption for the docking trial.

(f) Pilot ratings of the control system suitability (following NASA's Cooper Rating Scale), (Reference #1).

Mean angular rates are reported in the Results Section (Table II) for design information only and were not subjected to statistical analysis.

The four pilots completed a total of 117 successful docking trials under the various study conditions. Equal numbers of runs were not obtained under all of the study conditions, which was accounted for in the statistical analysis.

E. DATA ANALYSIS

Performance data derived from each of the 117 trials were analyzed to determine which of the performance measures were significantly influenced by the study conditions. The analysis of variance technique was used (Reference #2), which yields an overall comparison of the mean performance scores achieved under each of the study conditions. This allows for determination of whether the differences between these mean scores are "real" (i.e., significant) as opposed to chance differences based on sampling error. The probability level chosen for designating significance was the customary 5 percent confidence level (i.e., the differences found would be expected to re-occur in repeated samples 95 chances out of 100) correlations between pilot ratings and the performance measures were computed as well as the measure of agreement between pilots with respect to their evaluations.

In addition, a tabulation and analysis was made of the number of docking trials for which there was failure to meet the performance criteria.

III. RESULTS

The data were analyzed to provide answers to the following questions:

(1) Which attitude and translation control combinations result in significantly superior docking performance?

(2) Are there any significant differences between minimum pulse widths (15ms; 30ms) and between vehicle weights (light and heavy vehicle)?

(3) To what extent can the pilot remain within the required performance envelope that defines a successful docking maneuver?

The mean scores for 11 performance measures obtained under the study conditions are given in Table I. The figures in Appendix A are graphs of these mean scores and the standard deviations of values about them.

Table II shows the mean angular rates at docking for each of the attitude and translation control combinations.

Each of the study conditions had a statistically significant effect on at least one of the performance measures. The results of these effects were as follows:

(1) Control Combinations.

The difference between the mean scores for the four control combinations were significant for all 10 performance measures and the pilot ratings. It is apparent from Table I that the attitude hold control mode allows docking performance consistently superior to a minimum impulse attitude control system. In conjunction with the attitude hold control mode, a minimum impulse system for translation would be the combination of choice if only one fixed combination were permissible. However, where mode selection is possible, it would be logical to consider an attitude hold mode in conjunction with a direct translation mode for covering the longer distances to the CSM and then switching to minimum impulse translation for finer control at close range (e.g., 0 - 15 feet).

(2) Vehicle Weight.

Performance under the light and heavy vehicle configurations indicated that significantly less RCS fuel was consumed by the light vehicle over the 175 feet distance traveled. In addition, the light vehicle achieved greater terminal precision based on measures of vertical displacement ("h"). It would appear from observing pilot response during the trial, that this result stemmed from greater difficulty in making rapid correction of deviations with the heavier vehicle when nearing contact.

TABLE I

DOCKING PERFORMANCE MEASURES

(MEAN VALUES)

CONTROL COMBINATIONS ATTITUDE	TRANSLATION	TIME	RCS FUEL (LBS)	$\dot{h}$ ($\frac{FT}{SEC}$)	$\dot{s}$ ($\frac{FT}{SEC}$)	$\dot{z}$ ($\frac{FT}{SEC}$)	h (FT)	z (FT)	PITCH θ (°)	YAW ϕ (°)	ROLL ψ (°)	RATINGS
Attitude Hold	Direct	4.0	11.87	.10	.19	.05	.45	.14	3.5	.37	2.11	2.80
Attitude Hold	Min Impulse	4.5	7.02	.04	.16	.03	.19	.24	1.8	.51	1.60	2.63
Min Impulse	Direct	6.9	15.60	.14	.31	.12	.77	.59	5.0	3.81	4.39	5.29
Min Impulse	Min Impulse	8.0	9.35	.08	.14	.06	.76	.44	3.8	4.44	3.10	4.97
VEHICLE WEIGHT												
Light (4,210 pounds)		5.5	6.49	.08	.19	.07	.35	.35	3.1	2.41	3.22	3.92
Heavy (5,050 pounds)		6.3	9.21	.10	.21	.06	.73	.36	3.9	2.16	2.38	3.85
PULSE DURATION												
15 milliseconds		8.1	5.76	.05	.14	.04	.58	.27	3.5	3.5	2.60	3.81
30 milliseconds		7.4	9.94	.08	.15	.08	.99	.58	4.8	4.5	3.70	3.99

Indicates differences between the means of these conditions are statistically different

TABLE II

MEAN ANGULAR RATES IN THREE AXES

UNDER THE FOUR CONTROL COMBINATIONS (DEG/SEC)

	P-D	P-MI	MI-MI	MI-D
Pitch	.18	.08	.69	.80
Roll	.12	.22	.70	1.03
Yaw	.07	.05	.38	.36

(3) Pulse Duration.

Where significant superiority shows up between the two pulse durations, it is in favor of the shorter, 15 ms pulse. This occurs for RCS fuel consumption scores and lateral (z) deviations at contact (deviations in "h" indicate a trend but do not quite reach the required confidence level for significance). As might be expected there is also a significant interaction effect of vehicle weight and pulse duration on contact accuracy, such that the light vehicle in conjunction with the large (30 ms) resulted in significantly greater lateral deviations at contact.

Performance Criteria and Docking Success.

The extent to which the pilot failed to remain within the docking performance criteria are shown for information in Table III for each of 11 measures.

TABLE III

PERCENT FAILURE TRIALS TO MEET DOCKING CRITERIA

FOR ELEVEN PERFORMANCE MEASURES (N = 117 TRIALS)

Terminal Performance Measure	% Failure Trials	Terminal Performance Measure	% Failure Trials
Vertical Deviations (h)	15	Vertical Velocity ($\dot{h}$)	0
Lateral Deviations (z)	10	Lateral Velocity ($\dot{z}$)	0
Roll Angle Deviation (ψ)	5	Roll Rate (r)	11
Pitch Angle Deviation (θ)	6	Yaw Rate (p)	5
Yaw Angle Deviation (ϕ)	3	Pitch Rate (q)	15
Axial Velocity ($\dot{s}$)	0		

Performance Criteria and Docking Success - Cont'd

These occurrences of failure to meet the criteria were also tabulated under each of the four control combinations as shown in Table IV. A statistical analysis of these proportions indicates that these control conditions were significantly differentiated on the basis of failure occurrence (χ^2 = 20.7; $P < .01$).

TABLE IV

FAILURE TO MEET DOCKING CRITERIA

FOR ATTITUDE AND TRANSLATION CONTROL COMBINATIONS

	MI-MI (N = 35 trials)	MI-D (N = 34 trials)	P-MI (N = 32 trials)	P-D (N = 16 trials)
% Failure Trials	63%	68%	3%	25%

The pattern of failures closely follows the pattern of mean performance scores of Table I. Best performance (lowest failure occurrences) is shown for the attitude hold control mode with minimum impulse translation control. The attitude hold mode with direct translational control is next and these are sharply differentiated from the two control combinations utilizing the minimum impulse attitude control modes with direct or minimum impulse translation control.

Since the completion of the present study, revisions were made in criteria for docking contact velocities ($\dot{s}$, $\dot{h}$ and $\dot{z}$) (Reference #5). Percent of trials in which there was failure to meet the revised criteria were tabulated for the present study data and are as follows:

$\dot{s}$ = 2%; $\dot{h}$ = 3%; and $\dot{z}$ = 0%, compared to zero values for the original criteria

Little penalty is paid for the tighter velocity criteria, the differences being insignificant when compared to the values in Table II.

Pilot Ratings and Vehicle Performance.

In previous studies employing pilot ratings of vehicle control systems, (references #3 and #4), the reliability of a ten point adjectival scale (Cooper Ratings) has been shown to be fairly moderate (low .50's). Scale attenuation tends to reduce the chances of obtaining better reliability

Pilot Rating and Vehicle Performance - Cont'd

(i.e., the highest end of the scale or "1" category is never used , nor are the "9" and "10" categories, making this, in effect, a seven point scale).

The question also remains of how well these ratings correlate with pilot performance measures. If the ratings have a consistently high relationship to docking than there is justification for using the ratings as primary data rather than examining performance measures. Table IV shows the relationships between the pilot ratings and each of 9 performance measures and would certainly negate accepting the ratings as sufficiently equivalent to objective performance to justify their use in making design decisions.

TABLE V

MEASURES OF RELATIONSHIP BETWEEN

PILOT RATING AND DOCKING PERFORMANCE MEASURES

(N = 113)

Performance Measure	Correlation With Rating	Performance Measure	Correlation With Rating
Time	.58	ϕ	.54
z	.42	θ	.25
$\dot{z}$	.37	ψ	.26
h	.38	$\dot{s}$	.24
$\dot{h}$	.28		

All of the correlations are positive and differ significantly from zero correlation. However, the levels are uniformly low with only time, lateral displacement and yaw angle showing a fair degree of relationship. Rather than actually rating the vehicle control system per se, the pilots probably rate their overall docking performance. Trial time, lateral displacement and yaw angle were among the easiest values for the pilot to judge at the termination of a trial.

Trapeze Docking.

Of the degradation and failure conditions introduced under the trapeze docking technique, there was a complete inability to dock with rate feedback and attitude feedback loops removed from the attitude control system and utilizing the direct mode for the translation control. Under the same loss of feedback loops, but with a minimum impulse translation control, Trapeze Docking - Cont'd

docking could be accomplished, although erratically and with extreme difficulty.

With the rate feedback loop inoperable but the attitude feedback present, the system becomes too unstable to accomplish docking successfully.

All other combinations of degradation and failure conditions allowed for successful docking including on-off thrust in the proportional mode) (attitude hold mode) with feedback (see Figure #B10).

IV. DISCUSSION AND CONCLUSIONS

On the basis of the simulation utilized for the present study, there is little question that manual docking can be accomplished by the astronaut within the performance criteria established. Even the more stringent revised NASA criteria appear to present no problem.

More important for design purposes, however, is the determination of characteristic terminal performance values and the effectiveness of the different vehicle conditions studied. The conclusions that can be drawn from the results of this study are:

(a) Manual docking can be accomplished readily within the docking criteria established provided that the direct mode is not used for attitude control.

(b) The attitude hold mode, in conjunction with the minimum impulse translation control, would be the best combination for the terminal portions of the docking maneuver. The capability of selecting a direct translation mode at greater distances from the CSM should be considered in any future studies.

(c) For those performance measures significantly affected by vehicle weight (i.e., total RCS fuel consumption and vertical displacement) the Light vehicle (4,210 pounds) yielded superior performance to that obtained with the Heavy vehicle (5,050 pounds).

(d) The 15 ms pulse duration used in the minimum impulse translation mode resulted in significantly superior docking capability compared to the longer 30 ms pulse duration.

(e) Axial and lateral velocities at docking were well within the required limits.

V. FUTURE STUDY PLANS

For the GAEC Docking Simulation IA2 program, it is anticipated that the following areas of study will be considered:

(a) Attitude Control Loop - a pulse ratio modulation control scheme, which essentially consists of frequency modulation for small inputs changing to pulse width modulation for larger inputs. In addition, variations in the attitude hold dead zone for vehicle limit cycling will be considered.

(b) RCS Jet Failure - reaction jet failures (failing on and off) for a single jet and for a quad of jets with proper jet logic switching included.

(c) Overhead Docking Procedure - capability of accomplishing the docking maneuver with the LEM overhead docking hatch for various control conditions and for various docking procedures.

(d) Instrument Failure Conditions - ability to achieve docking with varying combinations of visual and instrument information including failure of particular displays such as the All Attitude Indicator.

(e) Visual Aids for Docking - effects of visual aids such as coded lights for attitude information, sighting reticles, probes and CSM markings for improving visual judgments and the accomplishment of the docking task.

(f) Translation Control Techniques - use of direct and minimum impulse translation control in conjunction with various attitude control mode conditions.

(g) Extendable Probe Technique - manual docking capability with an extendable probe under the vehicle dynamics and restraints imposed.

REFERENCES

1. Cooper, G.E., "Understanding and Interpreting Pilot Opinion," Reprint No. 683, IAS 25th Annual Meeting, January 28-31, 1957.

2. Cochran, W., and Cox, G., "Experimental Designs," 2nd Ed., New York, Wiley, 1957.

3. Freeberg, N., and Wolf, H., "Lunar Landing Simulation, Phase A: Preliminary Report #1," LED 480-2, Grumman Aircraft Engineering Corporation, May 17, 1963 (CONFIDENTIAL).

4. Freeberg, N., Wolf, H., and Berman, H., "Lunar Landing Simulation, Phase A: Preliminary Report #2," LED 480-5, Grumman Aircraft Engineering Corporation, August 19, 1963, (CONFIDENTIAL).

5. NASA, MSC, TWX to GAEC, #SCE-T356/63-62 of June 7, 1963.

6. Russo, J., "Detailed Pre-Simulation Report for Phase A Docking Simulation," LED-570-2, Grumman Aircraft Engineering Corporation, March 4, 1963, (CONFIDENTIAL)

7. Willman, J.L., "A Piloted Simulation Study of the Control Problems Encountered when Docking the LEM with the Apollo Command Module - Service Module Combination," Report NA 63H-409, North American Aviation, Inc., June 1963.

GLOSSARY OF SYMBOLS

A .... line of sight azimuth angle, deg

d .... controller deadband, deg

E .... line of sight elevation angle, deg

h .... relative vertical displacement, ft

$\dot{h}$ .... relative vertical velocity, ft/sec

$\ddot{h}$ .... relative vertical acceleration, ft/sec^2

I_{sp} .... specific impulse, 1/sec

I_{xx} .... inertia about x-axis, slug ft^2

I_{xy} .... inertia cross-product, slug ft^2

I_{xz} .... inertia cross-product, slug ft^2

I_{yy} .... inertia about y-axis, slug ft^2

I_{yz} .... inertia cross product, slug ft^2

I_{zz} .... inertia about z-axis, slug ft^2

K_1 .... forward loop gain, deg/in

K_A .... constant, 1/ft^2

K_R .... rate feedback gain, sec

$l_{1,2,3}$ .... direction cosines

M .... moment of inertia, slug ft^2

$m_{1,2,3}$ .... direction cosines

m_t .... thrust saturation point, deg

m .... LEM mass, slugs

$n_{1,2,3}$ .... direction cosines

n .... control system deadband, deg

p .... angular rate about X_B-axis, deg/sec

$\dot{p}$ .... angular acceleration about X_B-axis, deg/sec^2

q .... angular rate about Y_B-axis, deg/sec

$\dot{q}$ .... angular acceleration about Y_B-axis, deg/sec^2

r .... angular rate about Z_B-axis, deg/sec

$\dot{r}$ .... angular acceleration about Z_B-axis, deg/sec^2

S .... Laplace operator (1/sec)

s .... relative displacement in APOLLO orbital direction, ft

$\dot{s}$ .... relative velocity in APOLLO orbital direction, ft/sec

$\ddot{s}$ .... relative acceleration in APOLLO orbital direction, ft/sec^2

GLOSSARY OF SYMBOLS - Cont'd

t .... time, sec

T .... thrust, lbs

w .... minimum thrust level at instant of breakout from the system deadband, lbs

W_f .... fuel consumption, lbs

z .... relative lateral displacement, ft

$\dot{z}$ .... relative lateral velocity, ft/sec

$\ddot{z}$ .... relative lateral acceleration, ft/sec^2

δ .... stick displacement, inches

ϵ .... error signal for attitude control system, deg

ζ .... damping ratio

θ .... Euler pitch angle, deg

θ_v .... vehicle pitch angle, deg

ρ .... range, ft

$\dot{\rho}$ .... range rate, ft/sec

$\dot{\sigma}_A$ .... APOLLO orbital angular velocity, rad/sec

τ .... time constant, sec

ϕ .... Euler roll angle, deg

ϕ_v .... vehicle roll angle, deg

ψ .... Euler yaw angle, deg

ψ_v .... vehicle yaw angle, deg

ω_n .... natural frequency, rad/sec

σ .... $\sqrt{\frac{x^2}{N}}$ - standard deviation

$\bar{x}$ .... mean

SUBSCRIPTS

o .... initial condition

a .... actual

v .... vehicle

GLOSSARY OF SYMBOLS - Cont'd

ABBREVIATIONS

AAI .... all-attitude-indicator

CSM .... command-service-module

LEM .... lunar-excursion-module

MI .... minimum impulse

Prop .... proportional

APPENDIX A

MEANS AND STANDARD DEVIATIONS

OF DOCKING PERFORMANCE MEASURES

MEANS AND STANDARD DEVIATIONS
FOR TRIAL TIME

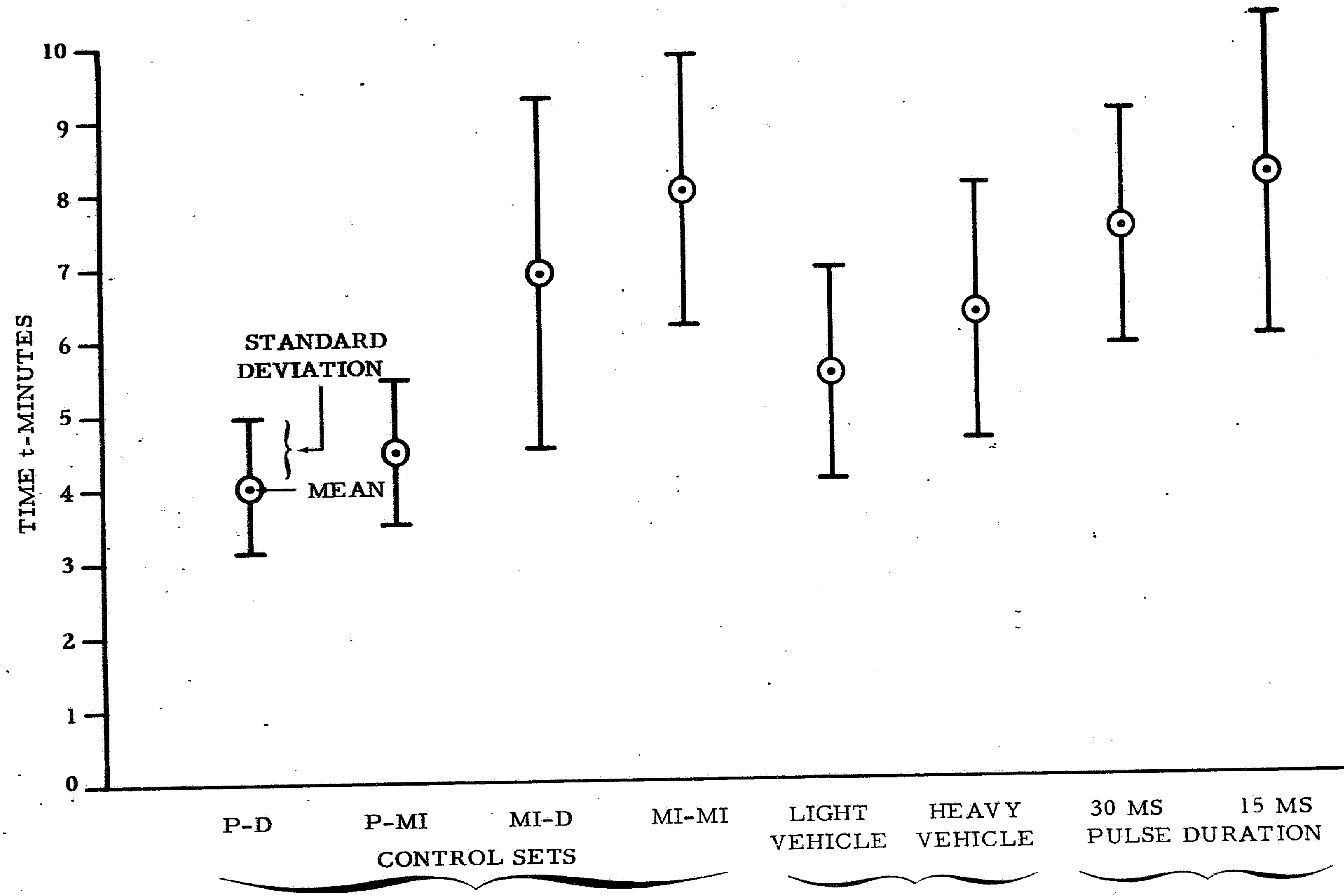


FIGURE A-1

MEANS AND STANDARD DEVIATIONS
FOR FUEL USED DURING TRIALS

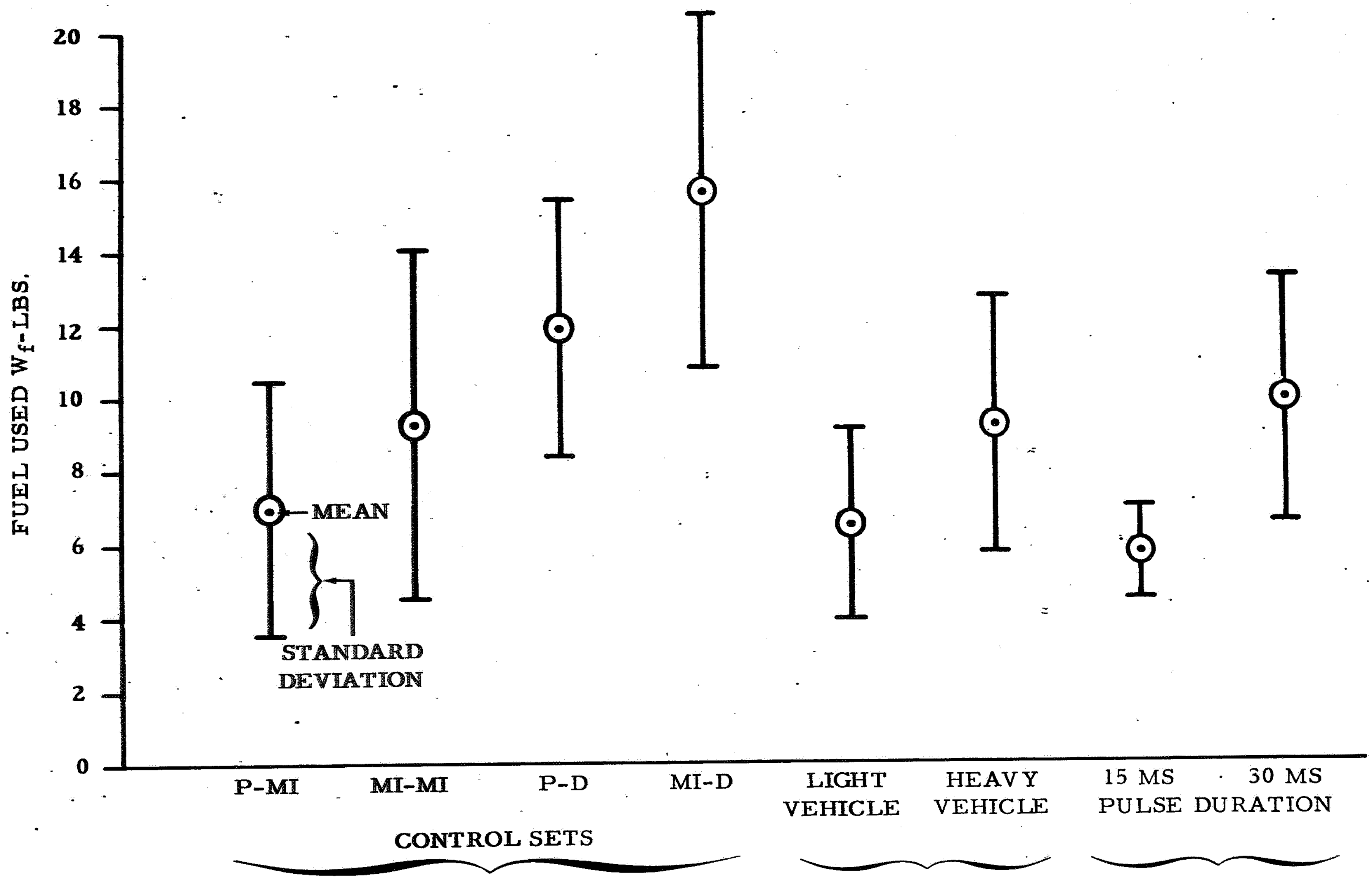


FIGURE A-2

MEANS AND STANDARD DEVIATIONS
FOR VERTICAL VELOCITY AT CONTACT

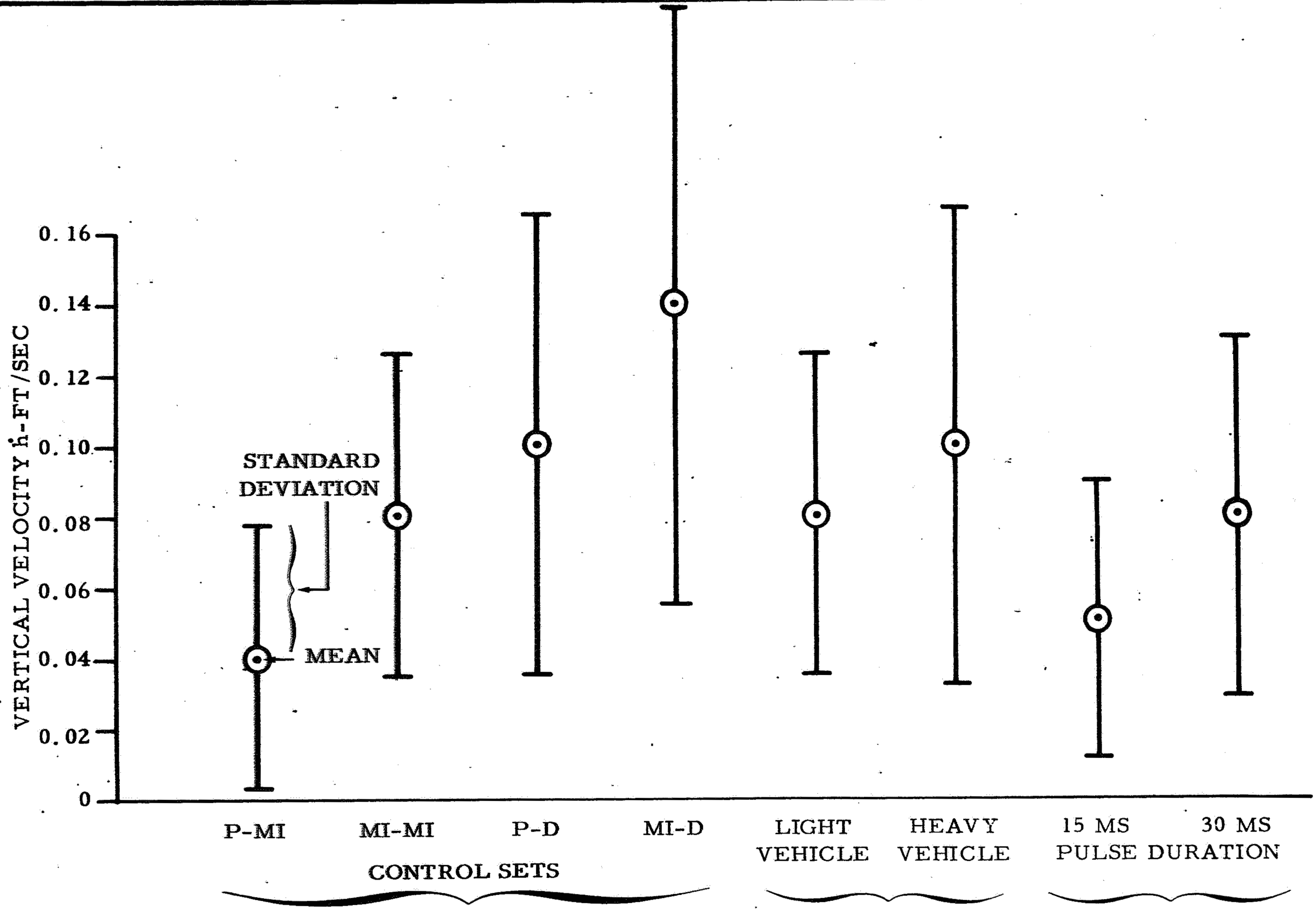


FIGURE A-3

MEANS AND STANDARD DEVIATIONS
CLOSING VELOCITY AT CONTACT

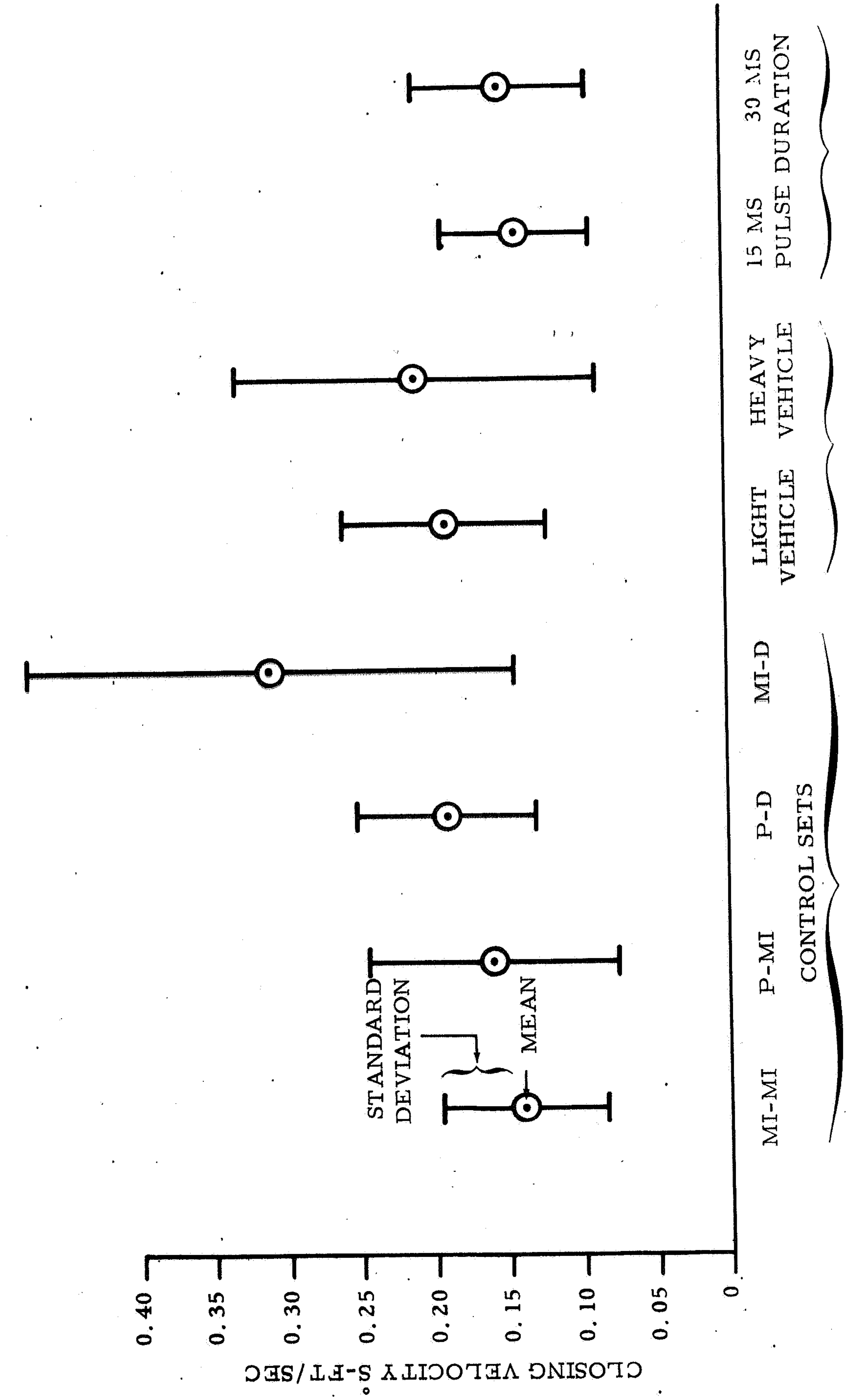


FIGURE A-4

MEANS AND STANDARD DEVIATIONS FOR LATERAL VELOCITY AT CONTACT

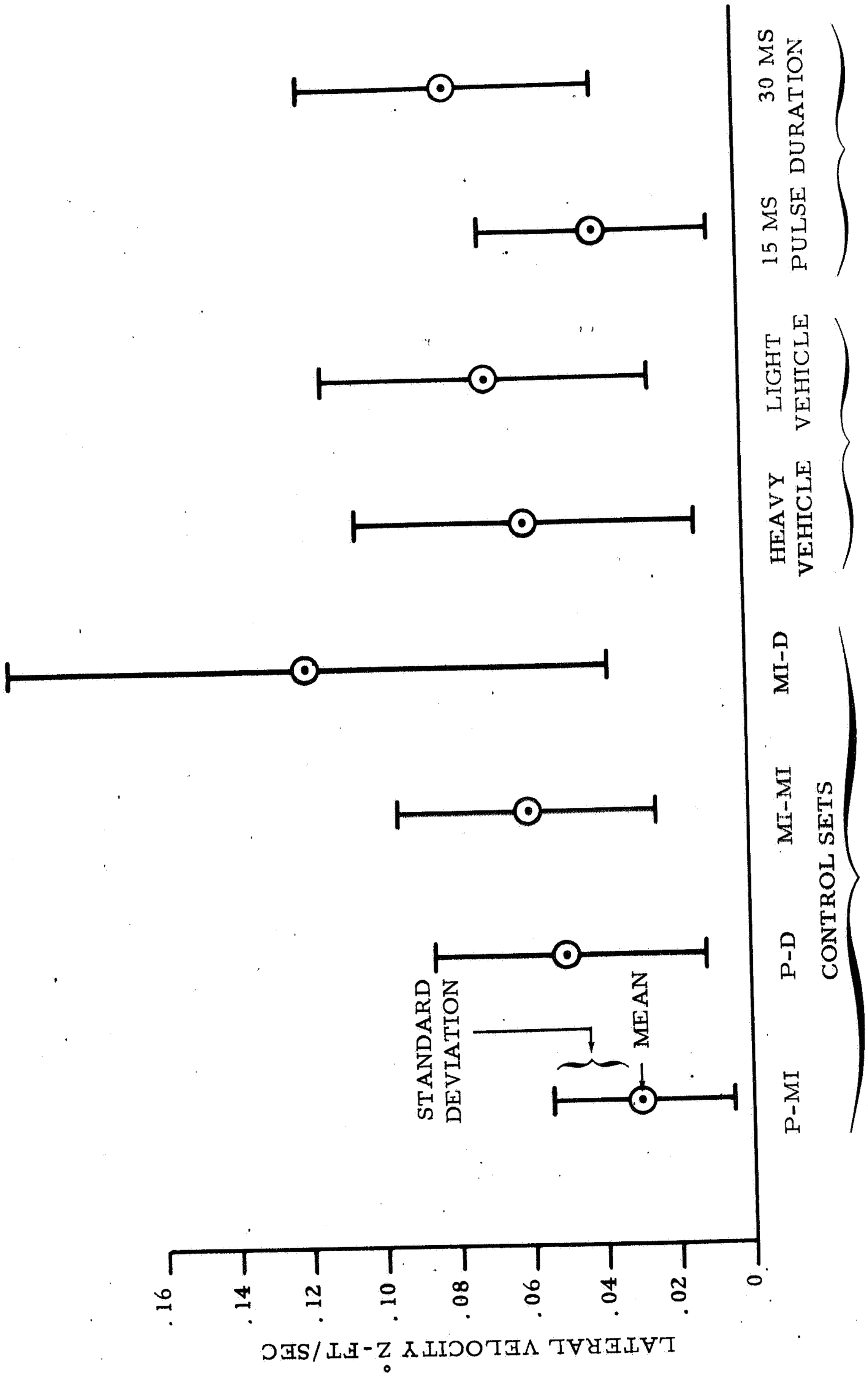


FIGURE A-5

MEANS AND STANDARD DEVIATIONS
FOR VERTICAL DISPLACEMENT AT CONTACT

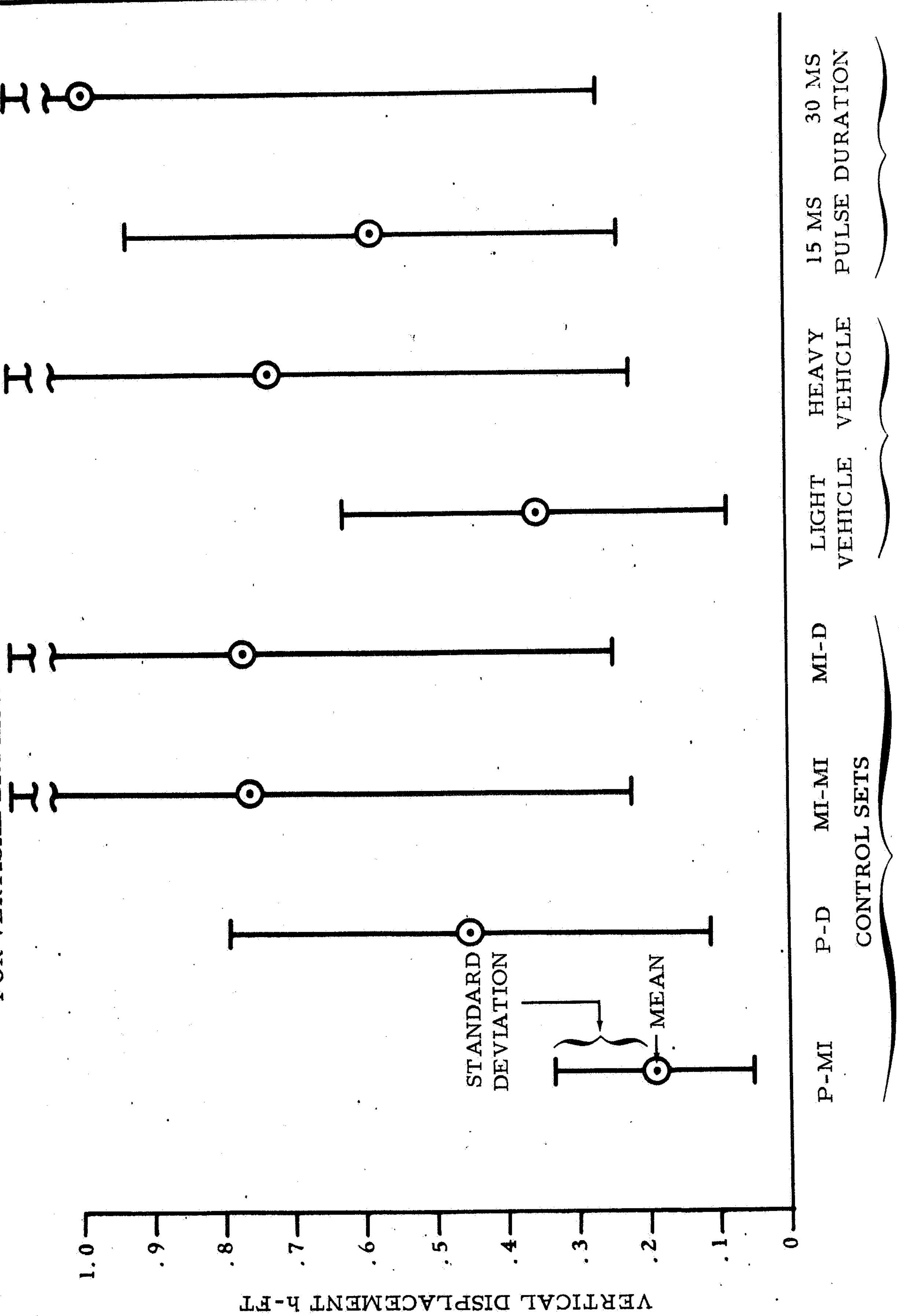


FIGURE A-6

MEANS AND STANDARD DEVIATIONS
FOR LATERAL DISPLACEMENT AT CONTACT

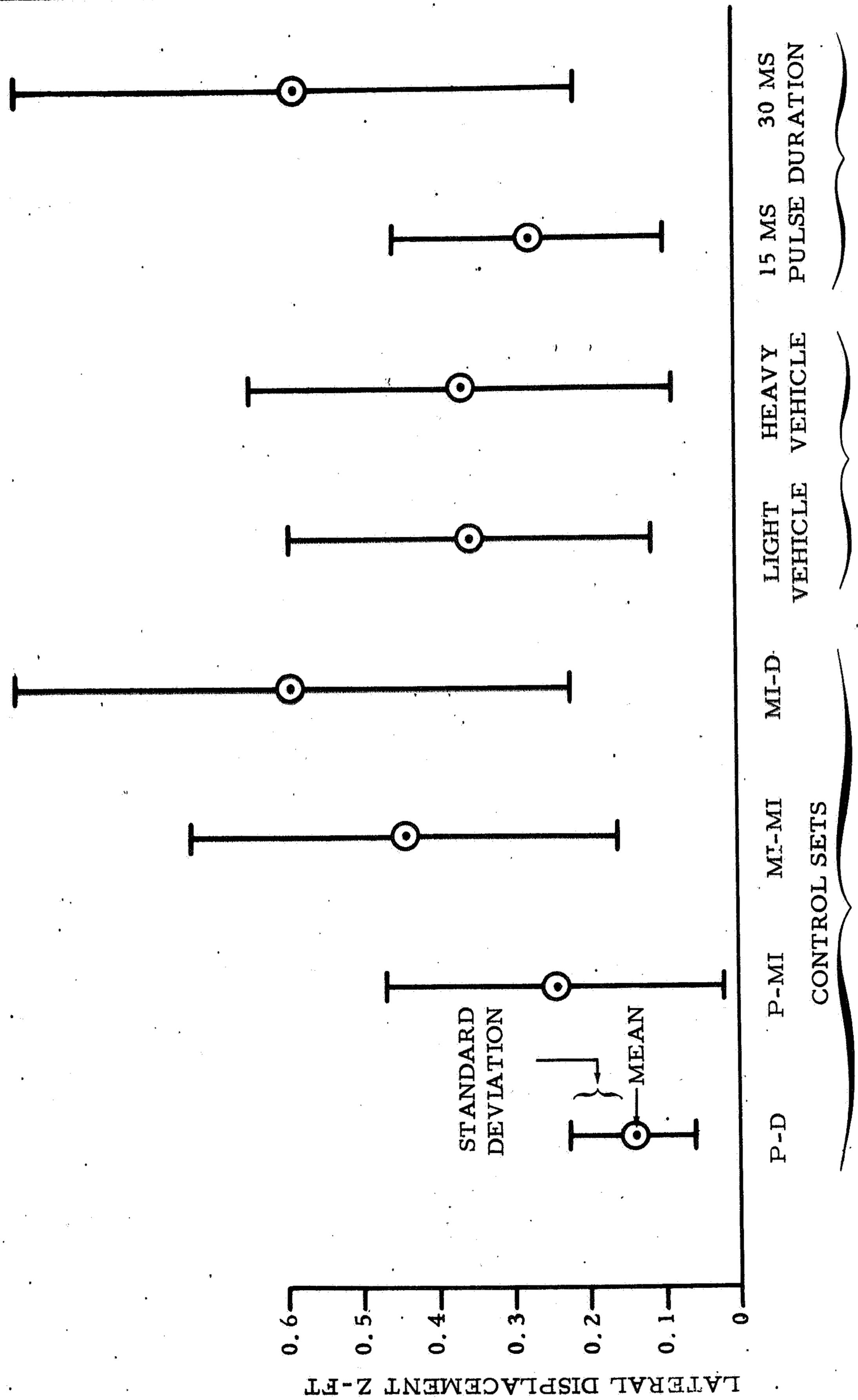


FIGURE A-7

MEANS AND STANDARD DEVIATIONS
FOR PITCH ANGLE AT CONTACT

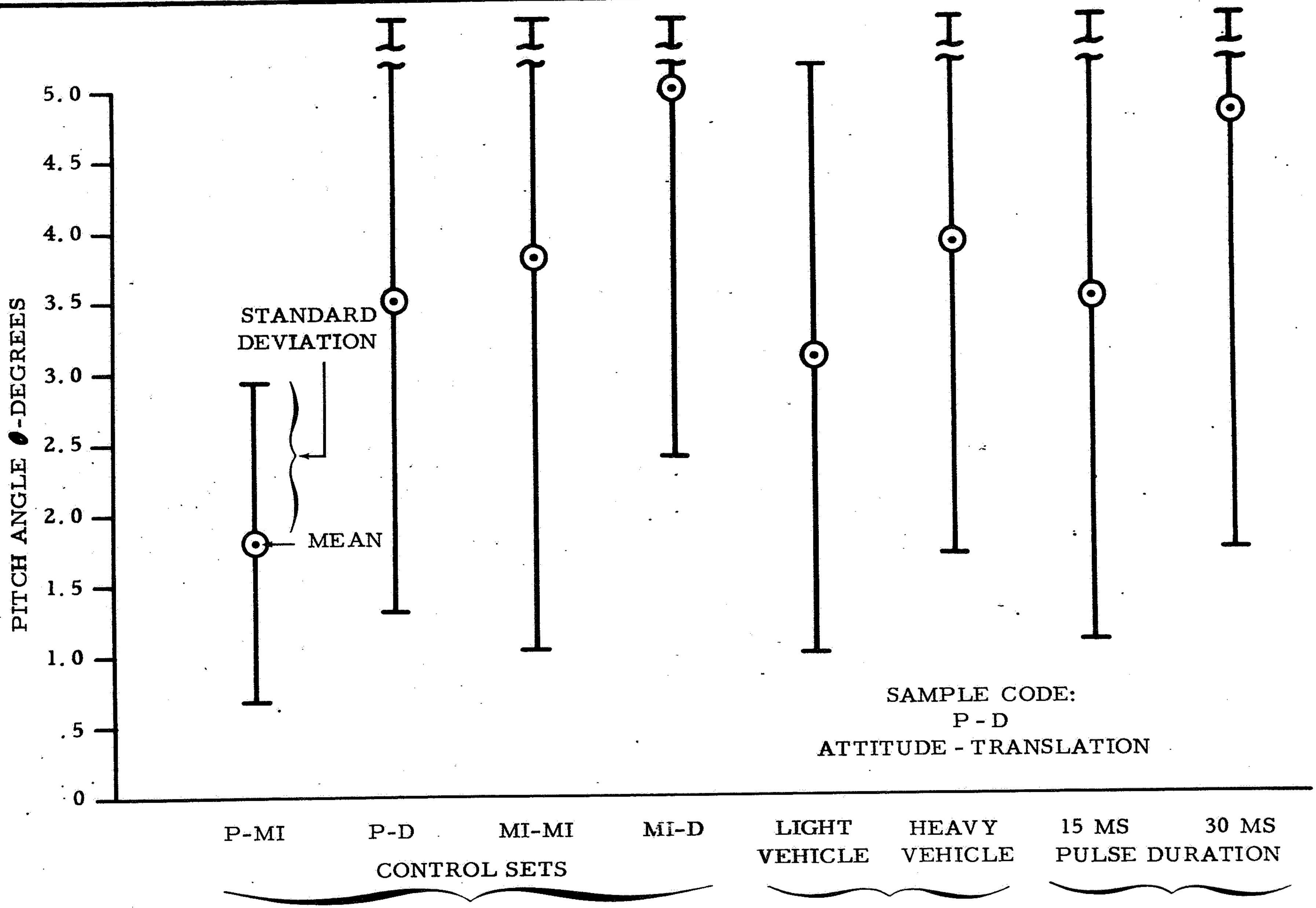


FIGURE A-8

MEANS AND STANDARD DEVIATIONS FOR PILOT YAW ANGLE AT CONTACT

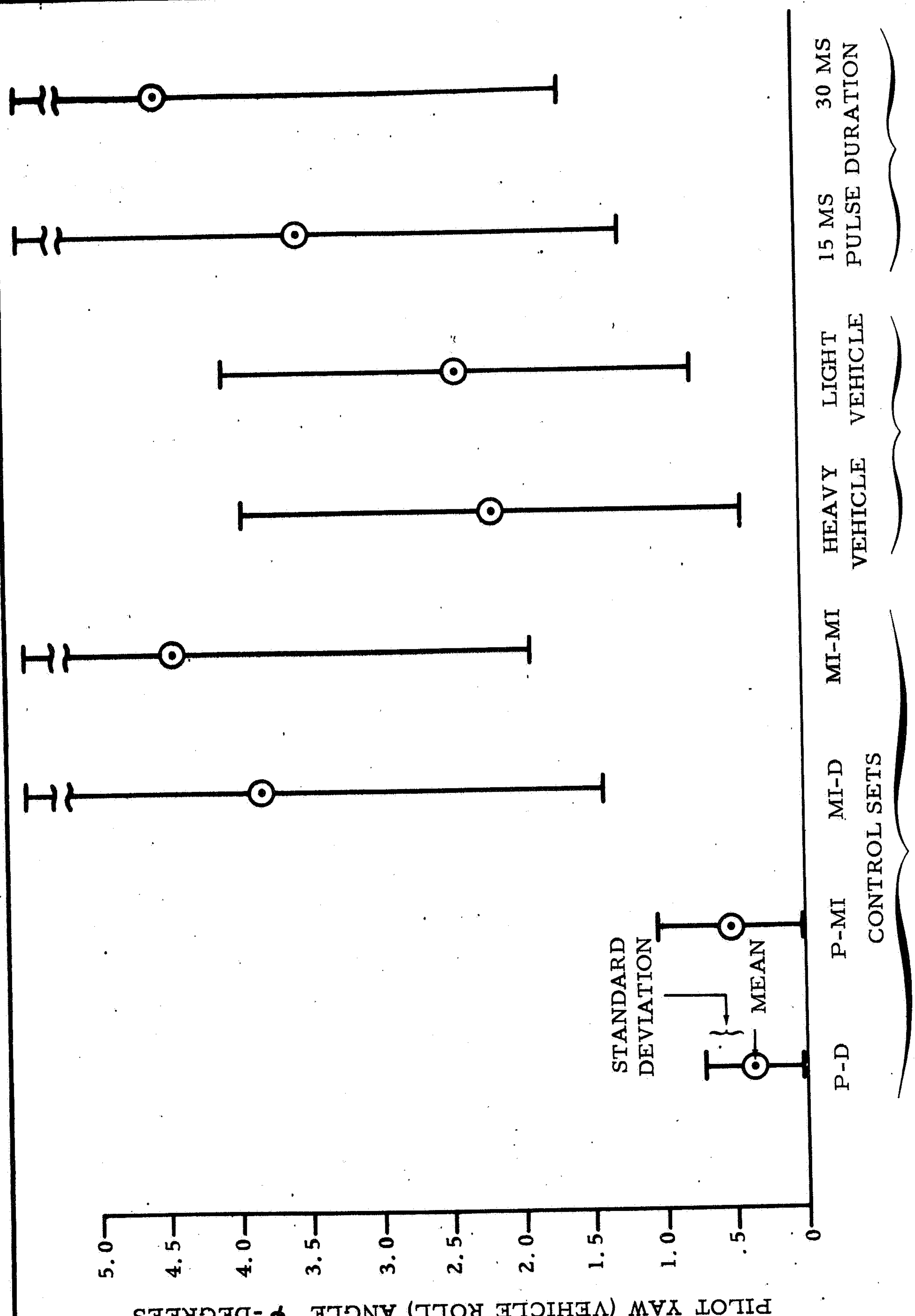


FIGURE A-9

MEANS AND STANDARD DEVIATIONS
FOR PILOT ROLL ANGLE AT CONTACT

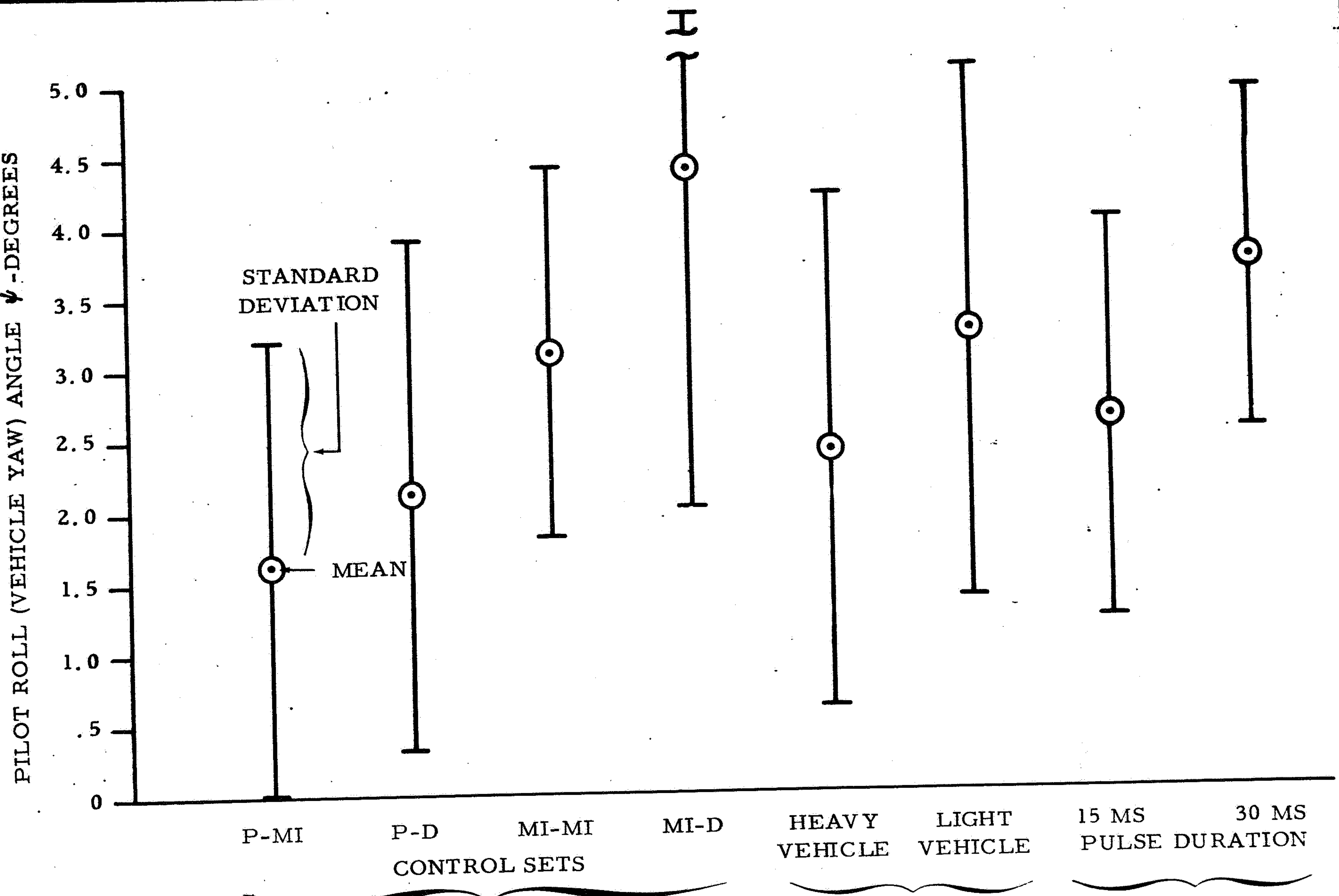


FIGURE A-10

MEAN PILOT OPINION COOPER RATINGS
& STANDARD DEVIATIONS

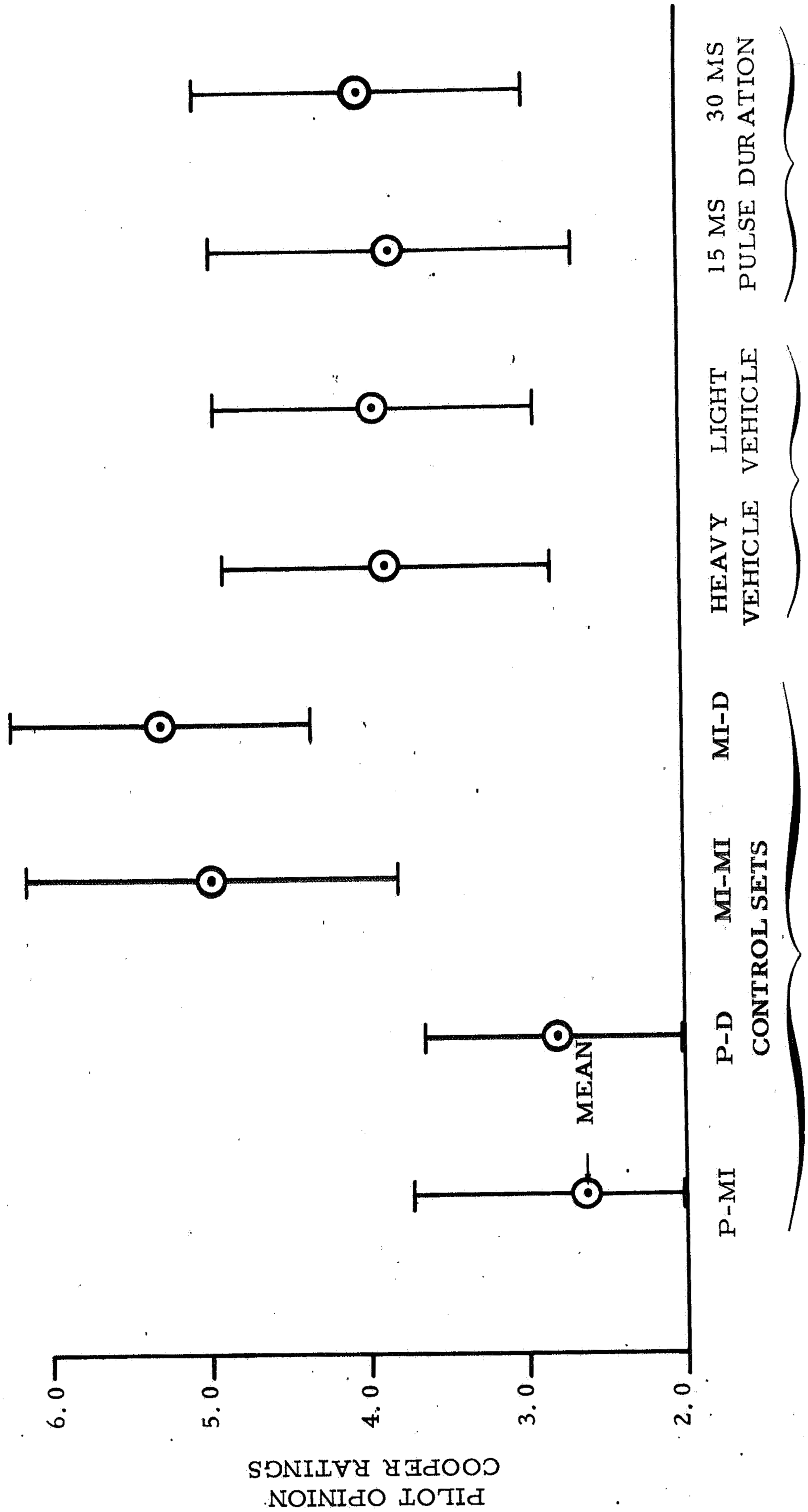


FIGURE A-11

APPENDIX B

SIMULATION PARAMETERS
AND EQUIPMENT DIAGRAMS

APPENDIX B

I. LEM BODY AXES ORIENTATION

Initially the LEM body axes were oriented as shown in Figure #B2-a. The vehicle was then rotated through the initial Euler angles to a position where the pilot faced the command module. The order of rotation was: a) $\Theta = +90^{\circ}$, b) $\phi = 180^{\circ}$. This positions the LEM body axes to the location shown in Figure #B2-c. From this point on, the computer reads the angles as starting at zero (0) degrees.

II. EULER ANGLE ORDER OF ROTATION

The Euler angle order of rotation was changed from the equations set up by GAEC in the Docking Presimulation report. The changes were from Θ_c, ψ_c, ϕ_c to ψ_c, Θ_c, ϕ_c in vehicle frame or ϕ_p, Θ_p, ψ_p in pilot frame (roll, pitch, yaw) because of the NAA rig setup.

III. ERRORS FOUND IN COMPUTER PROGRAM

Certain errors in the computer programming were found during and after the simulation study runs. The errors were corrected for the trapeze type docking, but were consistently present throughout all other data collection runs.

(a) In the $\overset{\circ}{q}$ equation (see Reference #6), there was a q^2 term in place of an r^2 term. The error only effected the heavy inertia set that had cross-coupling incorporated, and the magnitude of the error was small enough to be considered as negligible.

(b) The specific impulse used for all the runs made was 300 sec. The value that should have been used for pulsing was 200 sec.

(c) There was an error in sign in the $\overset{\circ}{\psi}c$ term (Pilot roll). The wrong equation used was $\overset{\circ}{\psi}c = (r - \overset{\circ}{\delta}_A h_2) + \Theta_c (p - \overset{\circ}{\delta}_A l_2)$. The correct equation was $\overset{\circ}{\psi}c = (r - \overset{\circ}{\delta}_A h_2) - \Theta_c (p - \overset{\circ}{\delta}_A l_2)$. The effect of the error on the results of the simulation was insignificant because the value of r and p was continuously changing from plus to minus and the actual value of the roll angle was very small throughout the runs.

(d) An error was uncovered in the sign of the LOS Azimuth and Elevation equations. The incorrect equations were:

$$A = \sin^{-1} \frac{hm_1 + Zm_2 + Sm_3}{\rho \cos E}$$

and

$$E = \sin^{-1} \frac{hl_1 + Zl_2 + Sl_3}{\rho}$$

III. (d) cont'd.

The correct equations are:

$$A = \sin^{-1} \left\{ \frac{h\, m_1 + Z\, m_2 - S\, m_3}{\rho \operatorname{Cos} E} \right\}$$

and

$$E = \sin^{-1} \left\{ \frac{h\, l_1 + Z\, l_2 - S\, l_3}{\rho} \right\}$$

The effect of the above errors were considered to have had no significant bearing on the results of the present simulation study since they did not feed information into the equations of motion.

VI. SIMULATION DETAIL INFORMATION

The remainder of Appendix B provides details of the simulation parameters and equipment.

SYMBOL	UNITS	VALUE SET A	VALUE SET B
θ	DEG	0	0
ϕ	DEG	0	0
ψ	DEG	0	0
p	DEG/SEC	0	0
q	DEG/SEC	.0475	.0475
r	DEG/SEC	0	0
s	FT	175	175
$\dot{s}$	FT/SEC	+.30	+.30
h	FT	10	10
$\dot{h}$	FT/SEC	-.30	-.30
z	FT	20	20
$\dot{z}$	FT/SEC	-.30	-.30
I_{xx}	SLUG-FT^2	2350	2820
I_{yy}	SLUG-FT^2	2200	2640
I_{zz}	SLUG-FT^2	1050	1297
I_{xy}	SLUG-FT^2	0	200
I_{xz}	SLUG-FT^2	0	500
I_{yz}	SLUG-FT^2	0	200
m	SLUGS	130.75	156.85

INITIAL CONDITIONS

TABLE B-1

AXIS	d (DEG)	f (SEC)	n (DEG)	m_t (DEG)	w (LBS)	K	K_R (SEC)	K_1 DEG/IN.
θ	2.5	.025	.13	1.282	10.14	1.0	.5	3.44
ψ	2.5	.025	.14	1.482	9.8	1.0	.30	2.58
ϕ	3.0	.025	.13	1.282	10.14	1.0	.80	20.6

CONTROL SYSTEM CONSTANTS

TABLE B-2

CONTROL MODES VARIATION

	ATTITUDE CONTROL		TRANSLATIONAL MODE	
	CONTROL MODE	PULSE DURATION (SEC.)	CONTROL MODE	PULSE DURATION (SEC.)
1	MINIMUM IMPULSE	.015	MINIMUM IMPULSE	.015
2	MINIMUM IMPULSE	.015	DIRECT	-
3	PROPORTIONAL	-	MINIMUM IMPULSE	.015
4	PROPORTIONAL	-	MINIMUM IMPULSE	.030
5	PROPORTIONAL	-	DIRECT	-
6	MINIMUM IMPULSE	.030	MINIMUM IMPULSE	.030
7	MINIMUM IMPULSE	.030	DIRECT	-

TABLE B-3

LOCATION OF LEM
WITH RESPECT TO CSM

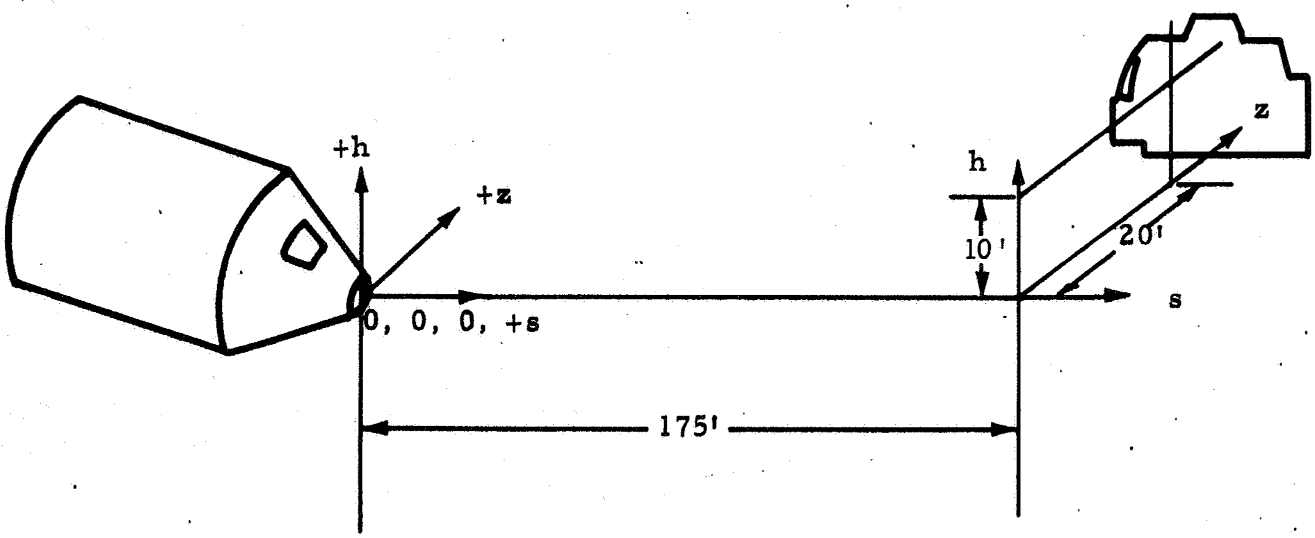
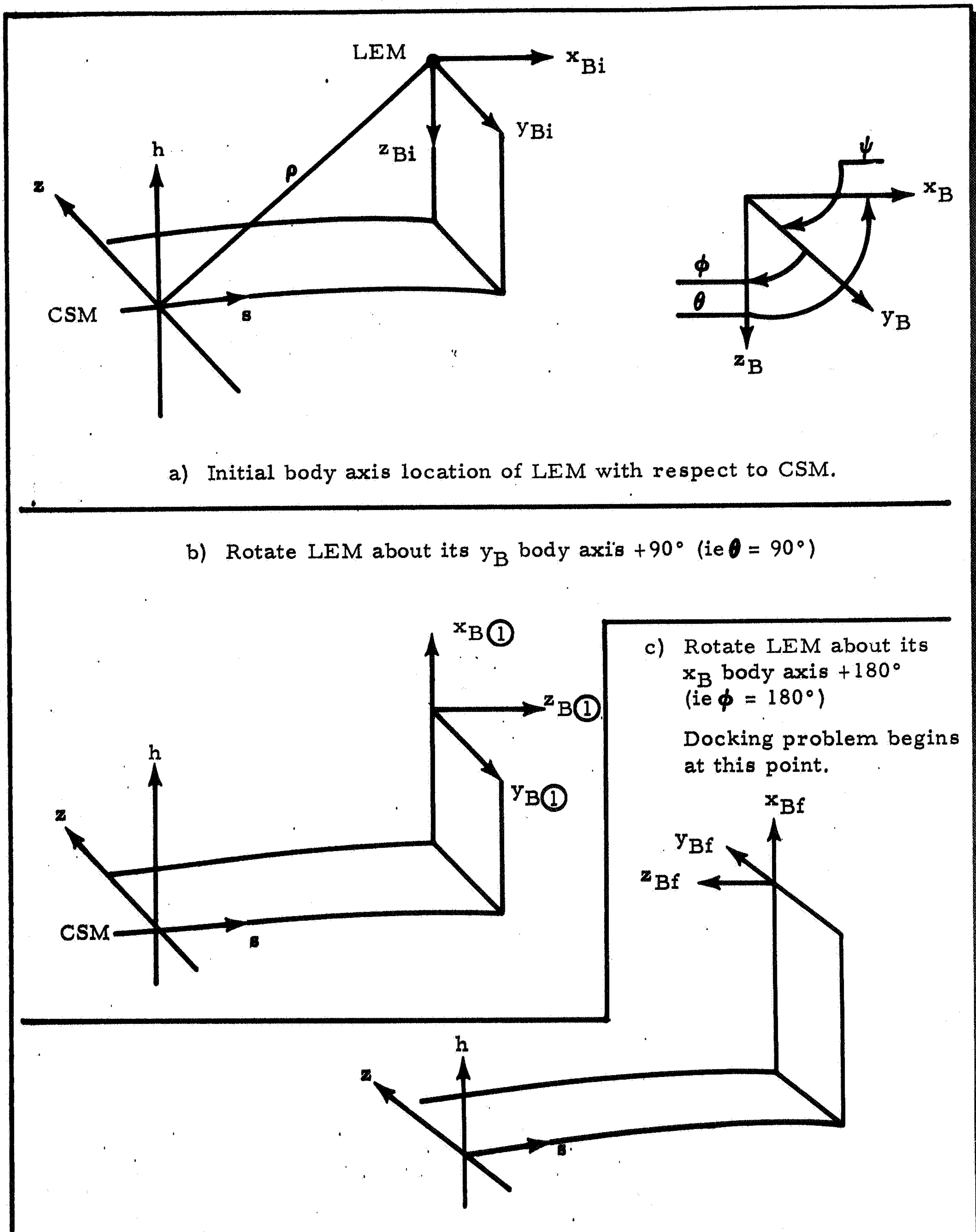


FIGURE B-1



ORIENTATION OF LEM WITH RESPECT TO CSM
FIGURE B-2

FLIGHT SIMULATOR COMPONENTS

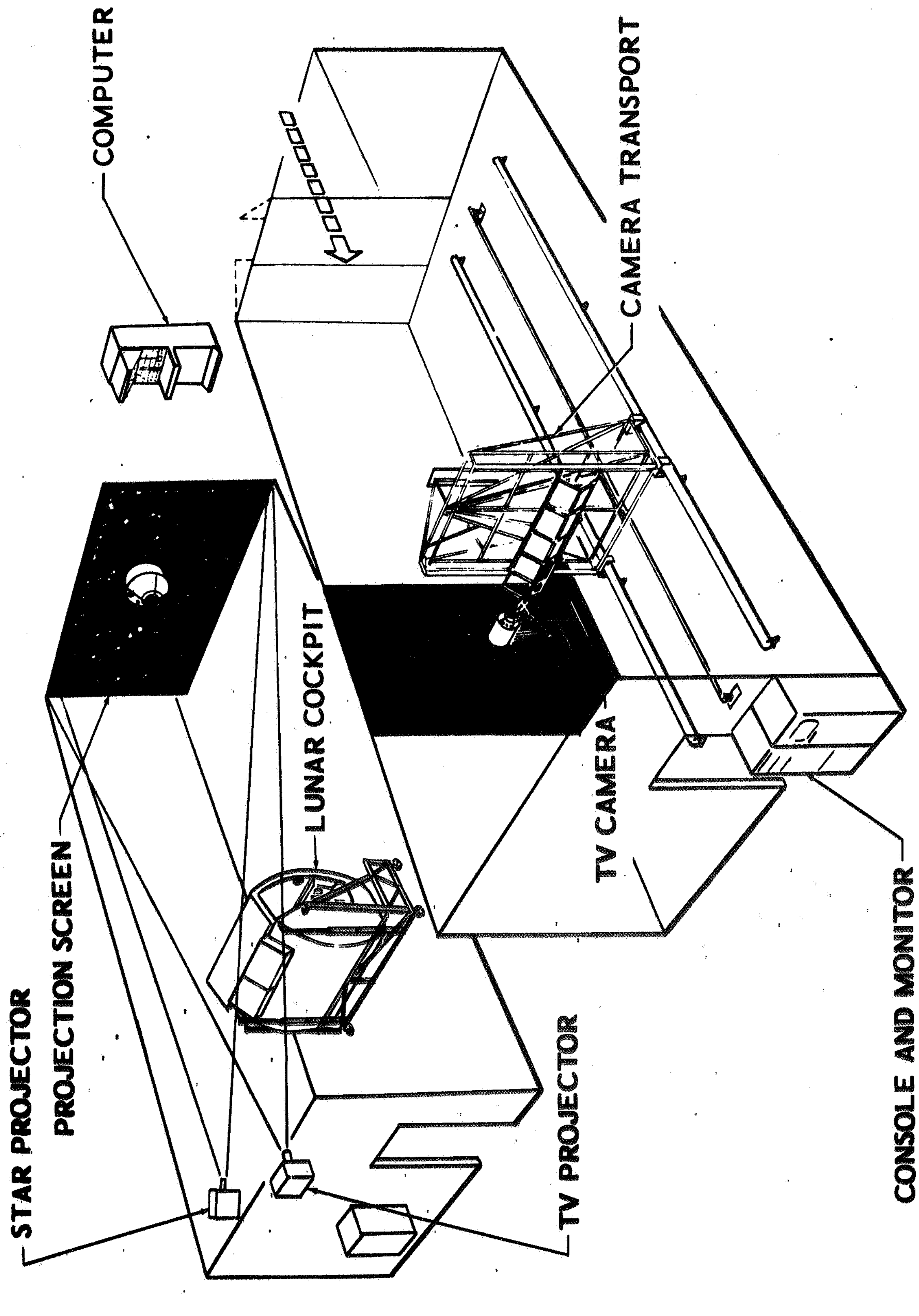
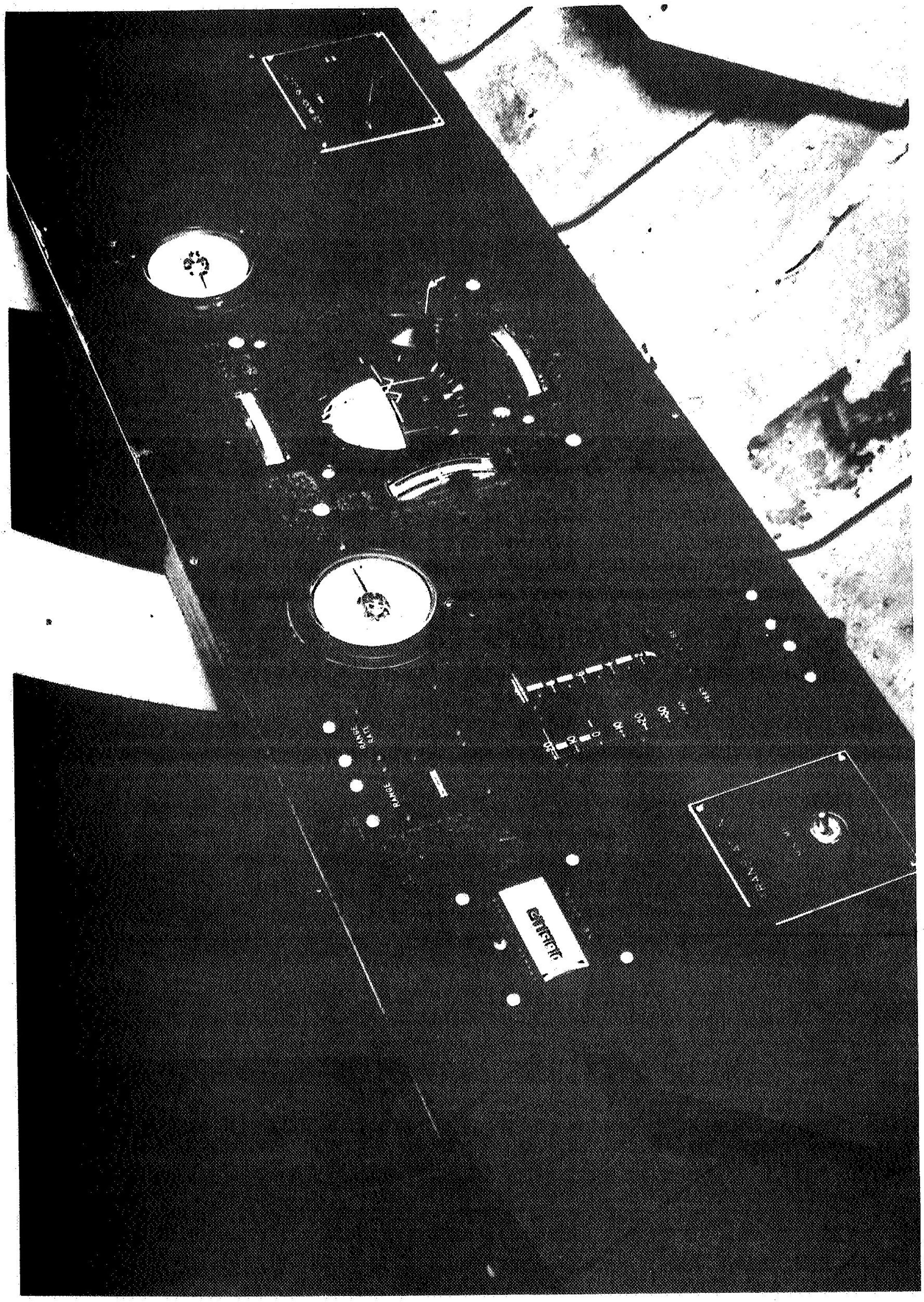


FIGURE B-3



COCKPIT INSTRUMENTATION

FIGURE B-4

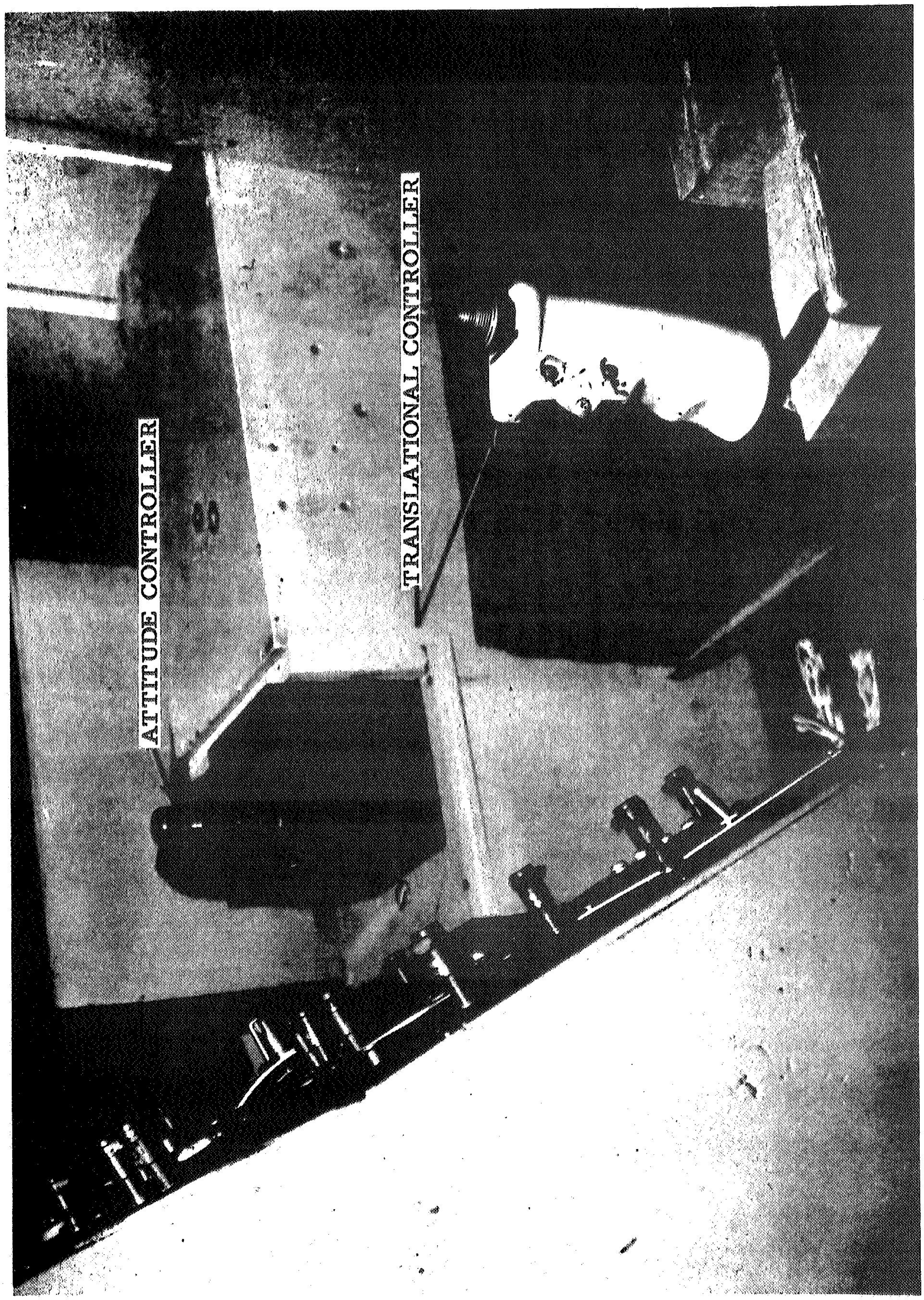


FIGURE B-5

CONTROLLERS

SIMULATOR FLOW DIAGRAM

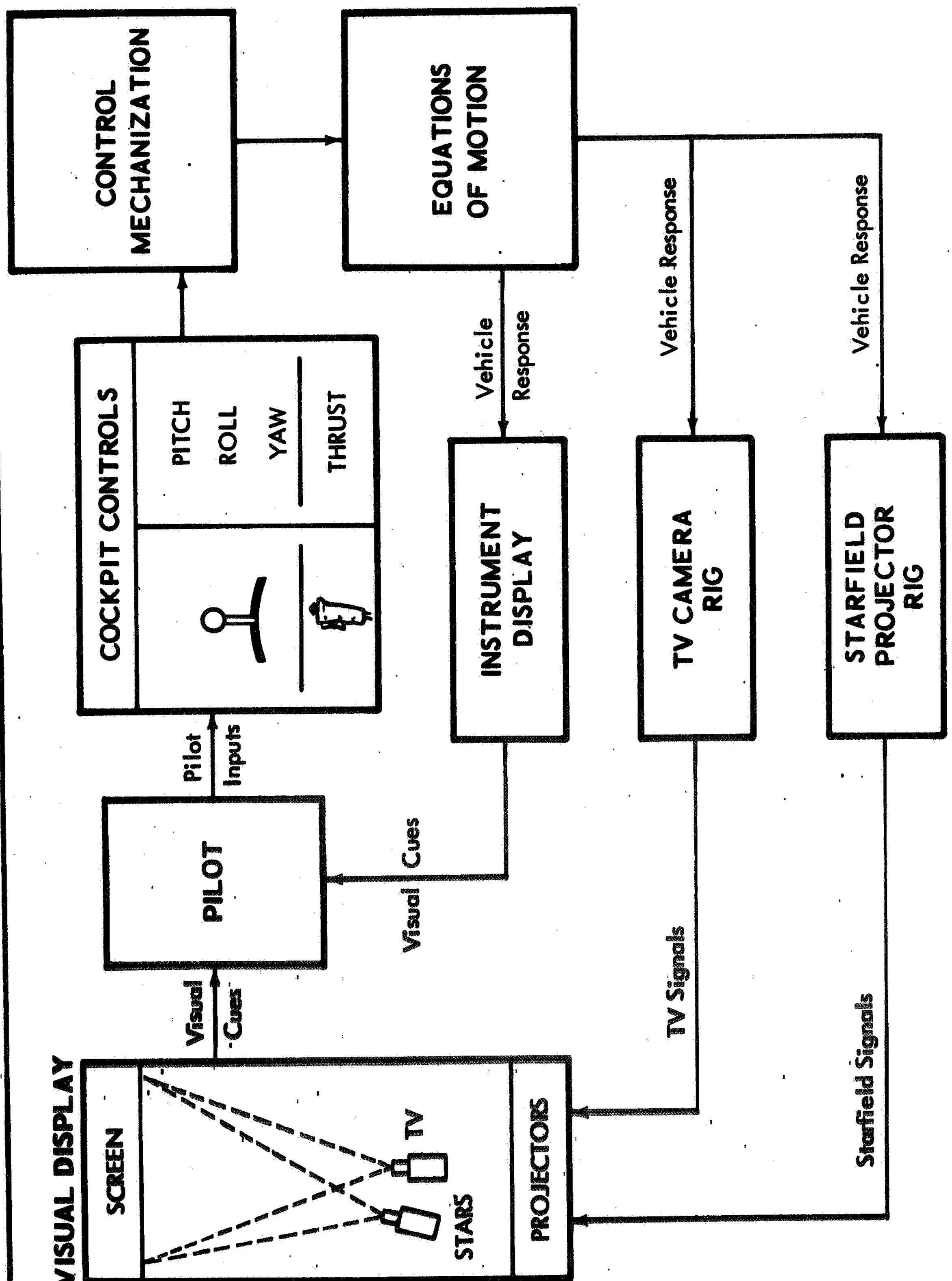
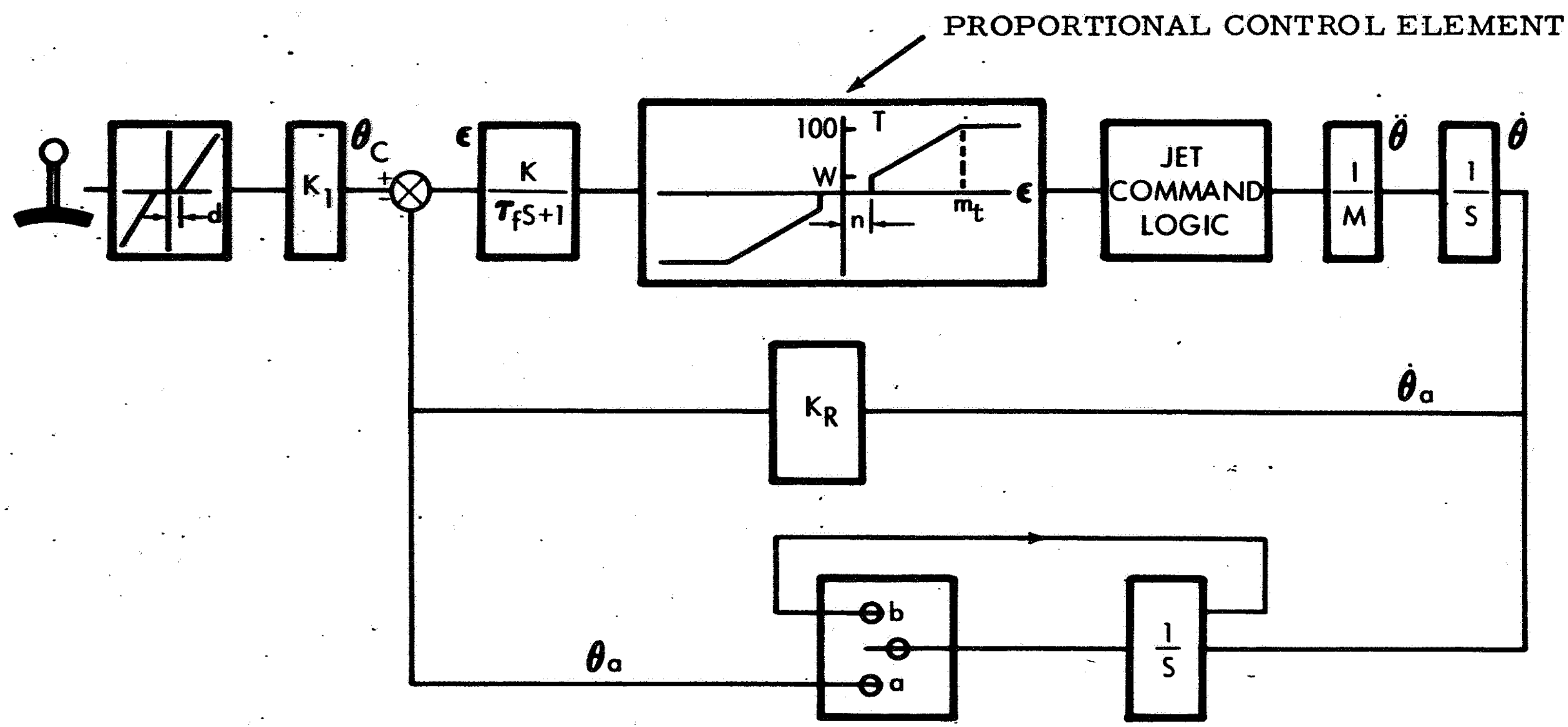


FIGURE B-6

PROPORTIONAL MODE

(RATE COMMAND WITH ATTITUDE - HOLD)



$\tau = .025$
$K = 1.0$

SWITCH POSITION
a – STICK WITHIN CONTROLLER DEADBAND
b – STICK OUTSIDE CONTROLLER DEADBAND

FIGURE B-7

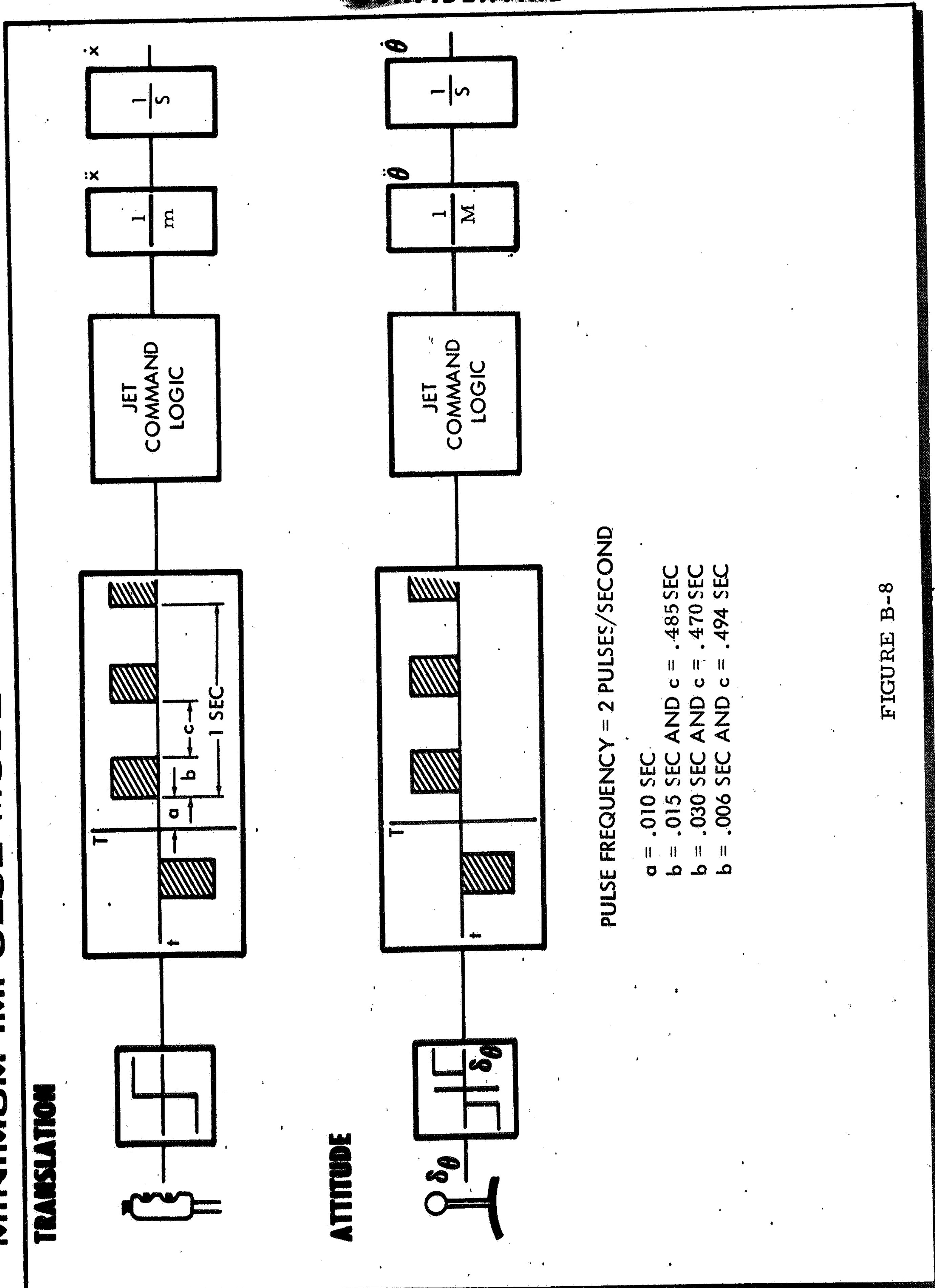

MINIMUM IMPULSE MODE
TRANSLATION
ATTITUDE
JET COMMAND LOGIC
JET COMMAND LOGIC
1/m
1/M
1/S
1/S
ẍ
ẋ
θ̈
θ̇
δ_θ
T
t
a
b
c
1 SEC
PULSE FREQUENCY = 2 PULSES/SECOND
a = .010 SEC
b = .015 SEC AND c = .485 SEC
b = .030 SEC AND c = .470 SEC
b = .006 SEC AND c = .494 SEC

FIGURE B-8

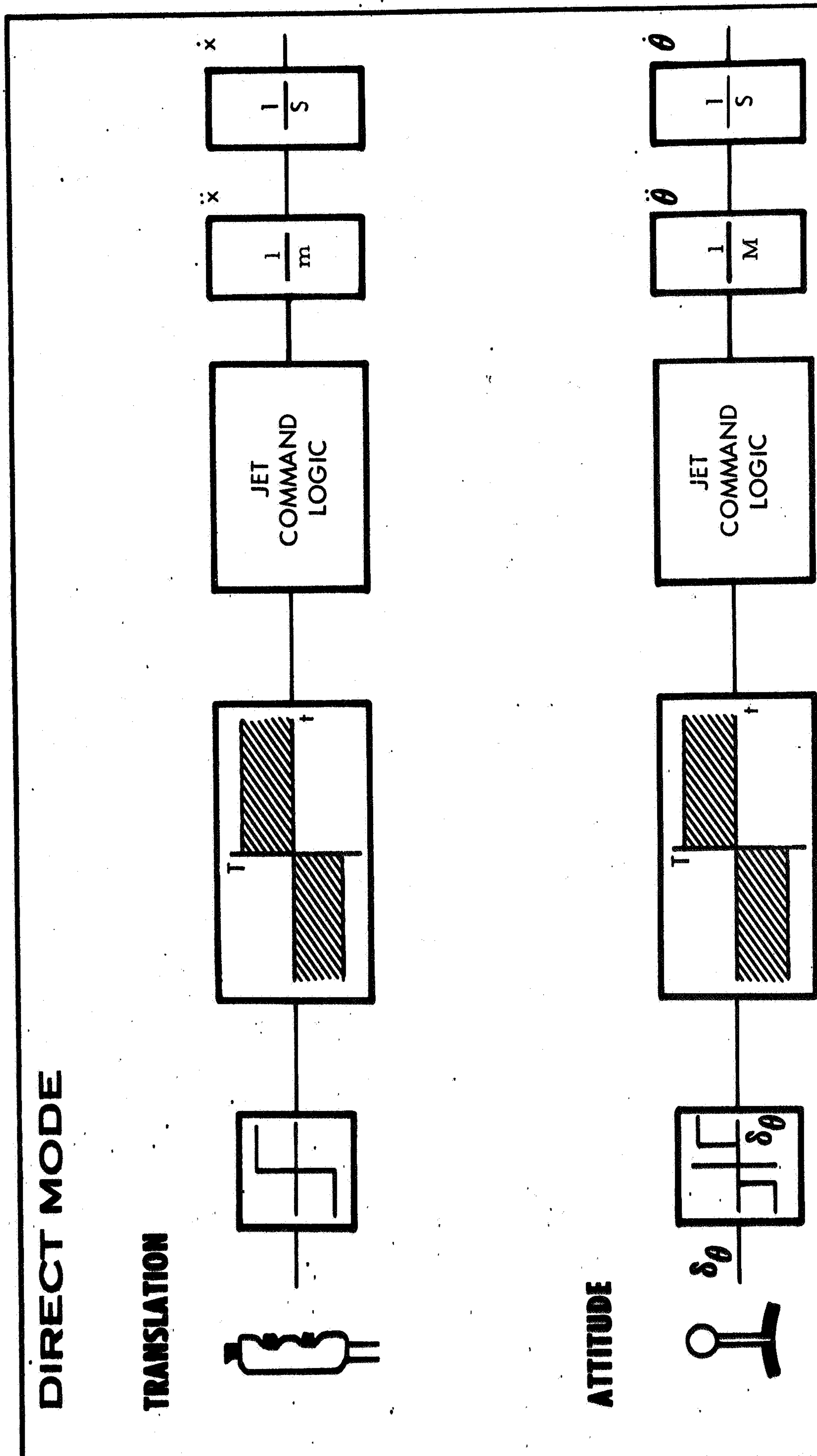

DIRECT MODE
TRANSLATION
ATTITUDE
JET COMMAND LOGIC
JET COMMAND LOGIC
T
t
T
t
δ_θ
δ_θ
$\frac{1}{m}$
$\ddot{x}$
$\frac{1}{S}$
$\dot{x}$
$\frac{1}{M}$
$\ddot{\theta}$
$\frac{1}{S}$
$\dot{\theta}$

FIGURE B-9

PROPORTIONAL MODE

(RATE COMMAND WITH ATTITUDE - HOLD)

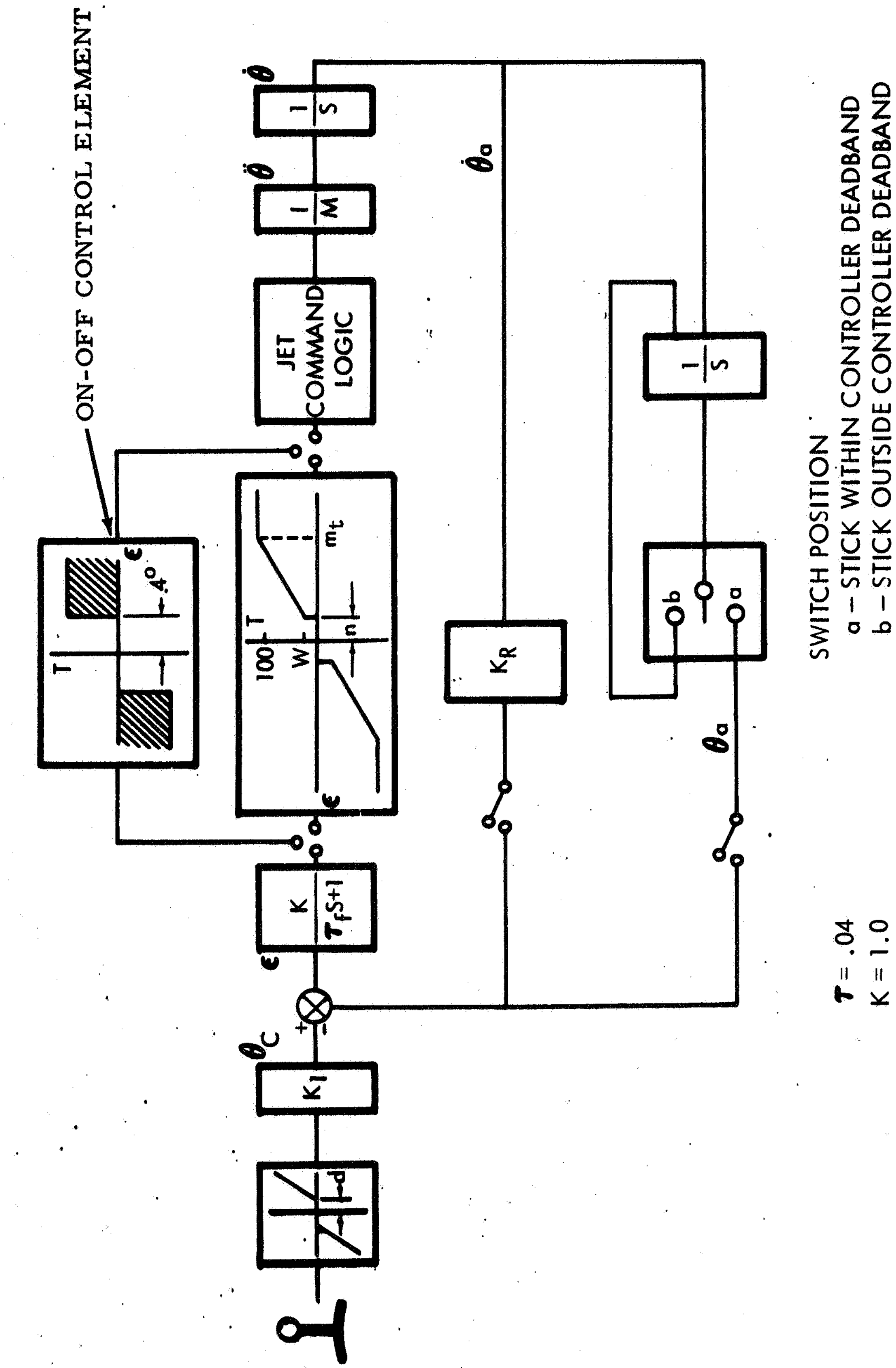
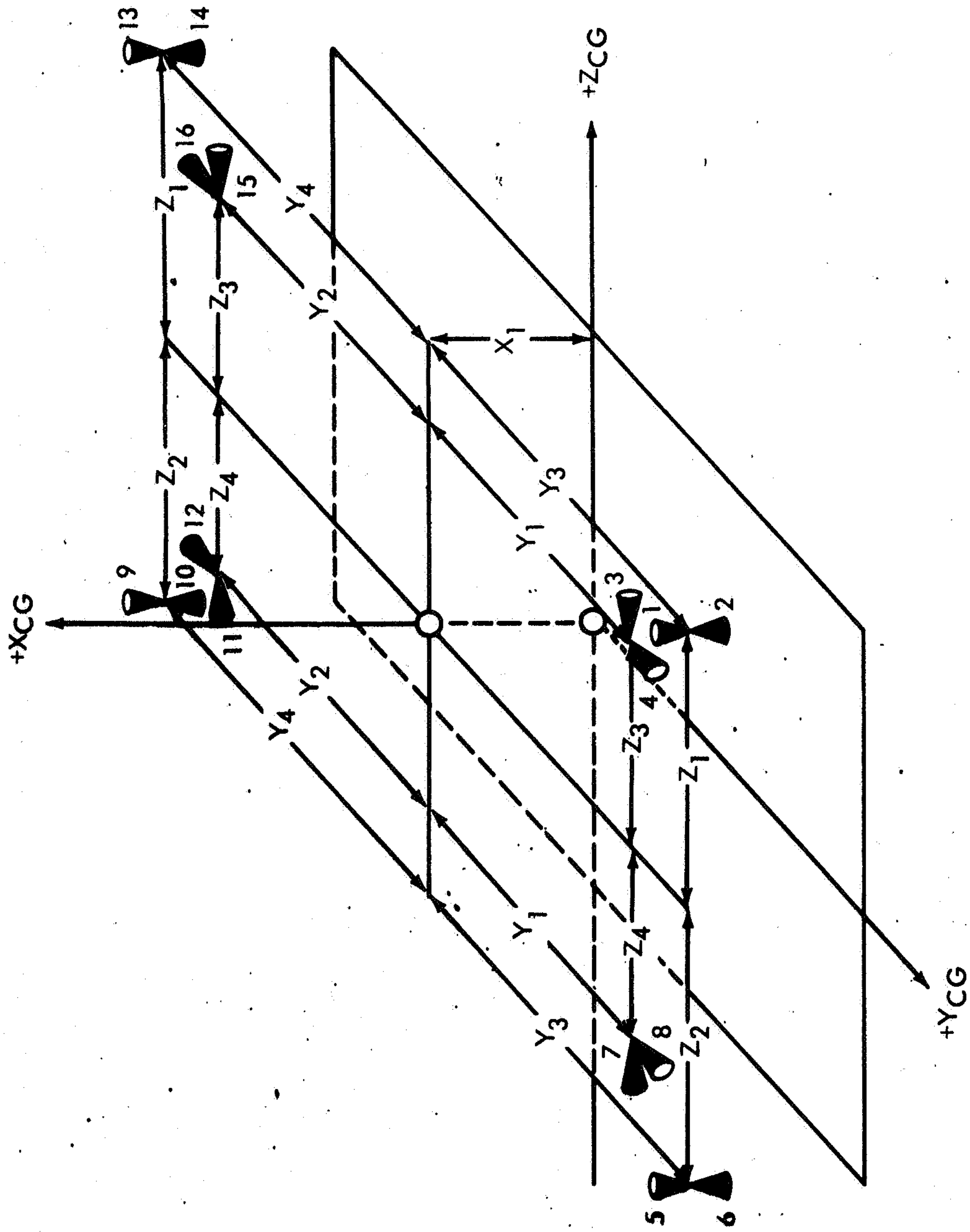


FIGURE B-10



REACTION JET GEOMETRY

FIGURE B-11